ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ

ΣΧΟΛΗ ΝΑΥΠΗΓΩΝ ΜΗΧΑΝΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ

ΔΙΑΤΜΗΜΑΤΙΚΟ ΜΕΤΑΠΤΥΧΙΑΚΟ ΠΡΟΓΡΑΜΜΑ ΣΠΟΥΔΩΝ

"ΝΑΥΤΙΚΗ ΚΑΙ ΘΑΛΑΣΣΙΑ ΤΕΧΝΟΛΟΓΙΑ ΚΑΙ ΕΠΙΣΤΗΜΗ"

"ΥΠΟΘΑΛΑΣΣΙΕΣ ΚΟΙΛΑΔΕΣ ΣΤΗ ΜΕΣΟΓΕΙΟ ΚΑΙ ΣΤΙΣ ΕΛΛΗΝΙΚΕΣ ΘΑΛΑΣΣΕΣ"

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

ΑΛΕΞΑΝΔΡΟΣ ΖΑΝΤΑΛΗΣ

ΕΠΙΒΛΕΠΩΝ ΚΑΘΗΓΗΤΗΣ: **ΚΑΨΙΜΑΛΗΣ ΒΑΣΙΛΕΙΟΣ**

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SCHOOL OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

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WAS APPOVED BY BELOW THREE-PARTY BOARD OF ENQUIRY

Vasilios Kapsimalis
Research Director
Institute of Oceanography
Hellenic Centre for Marine Research

Grigoris Rousakis
Senior Researcher
Institute of Oceanography
Hellenic Centre for Marine Research

George Zaraphonitis
Professor
School of Naval Architecture and Marine Engineering
National Technical University of Athens

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PREFACE

Submarine canyons have been the subject of research for along time. Shepard (1972) refers to a study from as early as the late nineteenth century, carried out by Milne (1897), which looked at the instability of canyon floor sediments as a possible cause for the repeated breaking of submarine cables that had been laid across a canyon. However, as a result of the steep terrain, locally enhanced current sand occasional down-canyon flushing events, the initial submarine canyon investigations were extremely challenging, and the number of studies was limited. Acoustic methods had to deal with excessives catter and noise, in-situ instruments were regularly washed away and the coarse canyon thalwegs and rocky walls proved difficult to sample. Direct observations were limited to shallow waters, within reach of divers or early submarines. With the increasing availability of new sampling and surveying technologies (deep-towed acoustic instruments, drop-down video systems, and eventually robotic vehicles), submarine canyon research increased dramatically. Particularly the advent of Remotely Operated Vehicles (ROVs) in many research institutes in the last 10years opened up a new perspective on submarine canyons, allowing a wider community of researchers to access parts of the deep ocean that had been hidden until then.

As a result of this increased research effort, our understanding of submarine canyons is gradually growing. A number of individual canyon systems have received considerable attention, but most canyons around the world have not yet been studied, or only to a very limited extend. Further- more, many of the studies carried out so far are focussing on one aspect (geology, geomorphology, sediment dynamics, hydrography, current patterns, mega-, macro-, meio fauna distribution, biogeochemistry…) of a single canyon or canyon system. The time seems right to start putting all those pieces of the jigsaw together, and to start looking at canyons in a more holistic way. To this end, the first International Symposiumon Submarine Canyons was organised in Brest, France in July2012. Canyon research from all over the world was presented, followed by cross-disciplinary discussions and networking.

The aim of this thesis is, taking into consideration various studies, to present the submarine canyons morfology and specially around Mediterranean Sea.

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CHAPTER 1

INTRODUCTION

1.1 General

Submarine canyons are incised into the continental shelf and slope of all continental margins and they act as conduits for the transfer of sediment from the continents to the deep sea. While belonging to the larger family of sea valleys, submarine canyons are a specific type of sea valley carved into the continental margin where they incise the slope and shelf, often off river mouths. In one of most noted study, Shepard (1963; 1981) recognized that submarine canyons may have several origins and restricted his definition to “steep-walled, sinuous valleys with V-shaped cross sections, axes sloping outward as continuously as river-cut land canyons and relief comparable to even the largest of land canyons”. This definition therefore excludes other seafloor valleys including: delta-front troughs (located on the prograding slope of large deltas), fan valleys (the abyssal, seaward continuation of submarine canyons some of which are remarkably long, slope gullies (incised into prograding slope sediments), fault valleys (structuralrelated, trough-shaped valleys, generally with broad floors), shelf valleys (incised into the shelf by rivers during sea level low stands, generally less than 120 m deep) and glacial troughs incised into the continental shelf by glacial erosion during sea level low stands, generally U-shaped in profile and having a raised sill at their seaward terminus. The heads of some submarine canyons terminate on the slope, making so-called “blind” or “headless” canyons. The largest canyons, however, commonly incise into the continental shelf and may even continue as shelf valleys that have a direct connection to modern terrestrial fluvial systems.

1.2 Importance

Early Interest in the evolution, occurrence and distribution of canyons in the World Ocean was initially driven by the need to lay cables and pipelines across the seafloor, to support naval submarine operations, to understand the geological evolution of continental margins as well as the oceanographic and biological processes associated with such features. In addition, depositional submarine fans may be found at the down-slope terminus of canyons together with their often extensive fan valley complexes which have been studied in detail as analogues for ancient deposits of economic significance for oil and gas exploration.

Oceanographic processes such as internal waves, coastally-trapped waves, the modification (e.g., bathymetric steering) of outer-shelf, and upper-slope geostrophic currents cause the mixing of canyon waters and upwelling of cold, nutrient-rich waters to the sea surface. For example, ocean mixing rates inside Monterey Canyon are as much as 1,000 times greater than rates measured in the open ocean. Canyons that incise the continental shelf have also been implicated in the local amplification of tsunami at the adjacent coastline. The upwelling and mixing associated with canyons enhance local primary productivity and the effects extend up the food chain to include birds and mammals. As a result, commercially important pelagic and demersal fisheries, as well as cetacean feeding grounds, are commonly located at the heads of submarine canyons.

Recent interest has focused on benthic habitats associated with submarine canyons, particularly the heads of shelf-incising canyons that are characterised by steep (vertical to overhanging) bedrock exposures where biologically diverse communities may settle. Submarine canyons that extend across the continental shelf and approach the coast are known to intercept organic-matter-rich-sediments that are transported along the inner shelf zone. It is such a process that causes organic rich material to be supplied to the head of Scripps Canyon and transported down-slope, where it provides nourishment for a diverse and abundant macrofauna. This also explains why seagrass was found at 3,400 m water depth at the base of Setubal Canyon off Portugal. Canyons that do not have a significant landward extension would presumably not intercept littoral sediments and would not be expected to contain such a rich biodiversity.

CHAPTER 2
SEAFLOOR MAPPING

Seafloor mapping, also called seabed imaging, is the measurement of water depth of a given body of water. Bathymetric measurements are conducted with various different methods, ranging from sonar and Lidar techniques to buoys and satellite altimetry. Various methods have advantages and disadvantages and the specific method used depends upon the scale of the area under study, financial means, desired measurement accuracy, and additional variables. Despite modern computer-based research, the ocean seabed in many locations is less measured than the topography of Mars.

2.1 History of seafloor mapping

At the beginning of the twentieth century mapping the seafloor was a very difficult task. The mapping of the sea floor started by using sound waves which were contoured into isobaths and early bathymetric charts of shelf topography provided the first insight into seafloor morphology. Due to horizontal positional accuracy and imprecise depth lead to mapping mistakes. It wasn't until the mid-twenties though, that the first achievements in visualizing the sea and ocean floors was made, when Marie Tharp, working alongside with Bruce Charles Heezen created the first three-dimensional physiographic map of the world's ocean basins in 1957.

Tharp's discovery was made at the perfect time. It was one of many discoveries that took place alongside with the invention of the computer. Computers with their ability to compute large quantities of data have made research conduction much easier. Researching the world oceans is no exception.

There has been a bloom in the underwater environmental exploration, because rather than just creating a map, scientists are trying to visualize the entire crust below in the maximum possible detail. This is where computers are put into good use. With their help researchers have managed to store and compute a large quantity of data enabling them to create the first digital map of the world ocean bed in 1970.The constantly developing technology allows computing to take place in the special equipment required for the so-called "high-resolution orthoimagery" which means that people no longer use sound frequencies to conduct marine exploration.

This method was later upgraded to Airborne Laser Bathymetry (ALB). In other words, this method just improves accuracy in the previous one. Another addition to this way of research is that images are not only of higher quality but have colour as well. The improvements of the research methods and the large amount of data received, stored and computed all lead to the creation of one of the first colour images of the underwater environment created on a computer.

2.2 Satellite imagery

Introduction

Another form of mapping the seafloor is through the utilisation of satellites. The satellites are equipped with hyper-spectral and multi-spectral sensors which are used to provide constant streams of images of coastal areas providing a more feasible method of visualising the bottom of the seabed.

Hyper-spectral sensors

The data-sets produced by Hyper-Spectral (HS) Sensors tend to range between 100-200 spectral bands of approximately 5 - 10 nm bandwidths. Hyper-Spectral Sensing, or imaging spectroscopy, is a combination of continuous remote imaging and spectroscopy producing a single set of data. Two examples of this kind of sensing are AVIRIS (Airborne visible/infrared imaging spectrometer) and HYPERION. More information on Hyper-Spectral Imaging can be found here (Hyperspectral imaging).

The application of HS sensors in regards to the imaging of the seafloor is the detection and monitoring of chlorophyll, phytoplankton, salinity, water quality, dissolved organic materials, and suspended sediments. However this does not provide a great visual interpretation of coastal environments.

Multi-spectral sensors

The other method of satellite imaging, multi-spectral (MS) imaging, tends to divide the EM spectrum into a small number of bands, unlike its partner Hyper-Spectral Sensors which can capture a much larger number of spectral bands. More information on multi-spectral sensing can be found at Multispectral image.

MS sensing is used more in the mapping of the seabed due to its fewer spectral bands with relatively larger bandwidths. The larger bandwidths allow for a larger spectral coverage, which is crucial in the visual detection of marine features and general spectral resolution of the images acquired.

High resolution orthoimagery

High resolution orthoimagery (HRO) is the process of combining of creating an image that combines the geometric qualities with the characteristics of photographs. The result of this process is an orthoimage, a scale image which includes corrections made for feature displacement such as building tilt. These corrections are made through the use of a mathematical equation, information on sensor calibration and the application of digital elevation models. More information on HRO and high resolution orthoimages can be found at orthophoto.

Execution of HRO

An orthoimage can be created through the combination of a number of photos of the same target. The target is photographed from a number of different angles to allow for the perception of the true elevation and tilting of the object. This gives the viewer an accurate perception of the target area.

Use in seafloor mapping

High resolution orthoimagery is currently being used in the 'terrestrial mapping program', the aim of which is to 'produce high resolution topography data from Oregon to Mexico'. The orthoimagery will be used to provide the photographic data for these regions.

2.3 Multibeam echosounder

A **multibeam echosounder** is a type of sonar that is used to map the seabed. Like other sonar systems, multibeam systems emit sound waves in a fan shape beneath a ship's hull. The amount of time it takes for the sound waves to bounce off the seabed and return to a receiver is used to determine water depth. Unlike other sonars, multibeam systems use beamforming to extract directional information from the returning soundwaves, producing a swath of depth readings from a single ping.

History and progression

Multibeam sonar sounding systems, also known as *swathe* (British English) or *swath* (American English), originated for military applications. The Sonar Array Sounding System (SASS) was developed in the early 1960s by the US Navy, in conjunction with General Instrument to map large swaths of the ocean floor to assist the underwater navigation of its submarine force. SASS was tested aboard the USS *Compass Island* (AG-153). The final array system, composed of sixty-one one degree beams with a swath width of approximately 1.15 times water depth, was then installed on the USNS *Bowditch* (T-AGS-21), USNS *Dutton* (T-AGS-22) and USNS *Michelson* (T-AGS-23).

Starting in the 1970s, companies such as General Instrument (now SeaBeam Instruments, part of L3 Klein) in the United States, Krupp Atlas (now Atlas Hydrographic) and Elac Nautik (now part of the Wärtsilä Corporation) in Germany, Simrad (now Kongsberg Maritime) in Norway and RESON in Denmark developed systems that could be mounted to the hull of large ships, and then small boats (as technologies improved and operating frequencies increased).

The first commercial multibeam is now known as the SeaBeam Classic and was put in service in May 1977 on the Australian survey vessel HMAS Cook. This system produced up to 16 beams across a 45-degree arc. The (retronym) term "SeaBeam Classic" was coined after the manufacturer developed newer systems such as the SeaBeam 2000 and the SeaBeam 2112 in the late 1980s.

The second SeaBeam Classic installation was on the French Research Vessel Jean Charcot. The SB Classic arrays on the Charcot were damaged in a grounding and the SeaBeam was replaced with an EM120 in 1991. Although it seems that the original SeaBeam Classic installation was not used much, the others were widely used, and subsequent installations were made on many vessels.

SeaBeam Classic systems were subsequently installed on the US academic research vessels USNS *Thomas Washington* (T-AGOR-10) (Scripps Institution of Oceanography, University of California), the USNS *Robert D. Conrad* (Lamont-Doherty Earth Observatory of Columbia University) and the RV *Atlantis II* (Woods Hole Oceanographic Institution).

As technology improved in the 1980s and 1990s, higher-frequency systems suitable for high-resolution mapping in shallow water were developed, and such systems are widely used for shallow-water hydrographic surveying in support of navigational charting. Multibeam echosounders are also commonly used for geological and oceanographic research, and since the 1990s for offshore oil and gas exploration and seafloor cable routing.

In 1989, Atlas Electronics (Bremen, Germany) installed a second-generation deep-sea multibeam called Hydrosweep DS on the German research vessel Meteor. The Hydrosweep DS (HS-DS) produced up to 59 beams across a 90-degree swath, which was a vast improvement and was inherently ice-strengthened. Early HS-DS systems were installed on the RV *Meteor (1986)* (Germany), the RV *Polarstern* (Germany), the RV *Maurice Ewing* (US) and the ORV *Sagar Kanya* (India) in 1989 and 1990 and subsequently on a number of other vessels including the RV *Thomas G. Thompson* (US) and RV *Hakurei Maru* (Japan).

As the cost of components has decreased, the number of multibeam systems sold and in operation worldwide has increased significantly. Smaller, portable systems can be operated on a small launch or tender vessel unlike the older systems that required considerable time and effort to attach to a ship's hull. Some multibeam echosounders such as the Teledyne Odom MB2 also incorporate a motion sensor at the face of the acoustic transducer, allowing even faster installation on small vessels. Multibeam echosounders like this are allowing many smaller hydrographic survey companies to move from traditional single beam echosounders to swath systems.

Multibeam data includes bathymetry, acoustic backscatter, and water column data. Gas plumes now commonly identified in midwater multibeam data are termed flares.

Figure 1 A multibeam echosounder showing the transmit array (larger black rectangle) and receive array (narrower rectangle) - Odom MB1

Theory of operation

A multibeam echosounder is a device typically used by hydrographic surveyors to determine the depth of water and the nature of the seabed. Most modern systems work by transmitting a broad acoustic fan shaped pulse from a specially designed transducer across the full swath acrosstrack with a narrow alongtrack then forming multiple receive beams (beamforming) that are much narrower in the acrosstrack (around 1 degree depending on the system). From this narrow beam, a two way travel time of the acoustic pulse is then established utilizing a bottom detection algorithm. If the speed of sound in water is known for the full water column profile, the depth and position of the return signal can be determined from the receive angle and the two-way travel time.

In order to determine the transmit and receive angle of each beam, a multibeam echosounder requires accurate measurement of the motion of the sonar relative to a cartesian coordinate system. The measured values are typically heave, pitch, roll, yaw, and heading.

To compensate for signal loss due to spreading and absorption a time-varied gain circuit is designed into the receiver.

For deep water systems, a steerable transmit beam is required to compensate for pitch. This can also be accomplished with beamforming.

2.4 Side scan sonar

Side-scan sonar (also sometimes called **side scan sonar**, **sidescan sonar**, **side imaging sonar**, **side-imaging sonar** and **bottom classification sonar**) is a category of sonar system that is used to efficiently create an image of large areas of the sea floor.

Work principle

Side-scan uses a sonar device that emits conical or fan-shaped pulses down toward the seafloor across a wide angle perpendicular to the path of the sensor through the water, which may be towed from a surface vessel or submarine. The intensity of the acoustic reflections from the seafloor of this fan-shaped beam is recorded in a series of cross-track slices. When stitched together along the direction of motion, these slices form an image of the sea bottom within the swath (coverage width) of the beam. The sound frequencies used in side-scan sonar usually range from 100 to 500 kHz; higher frequencies yield better resolution but less range.

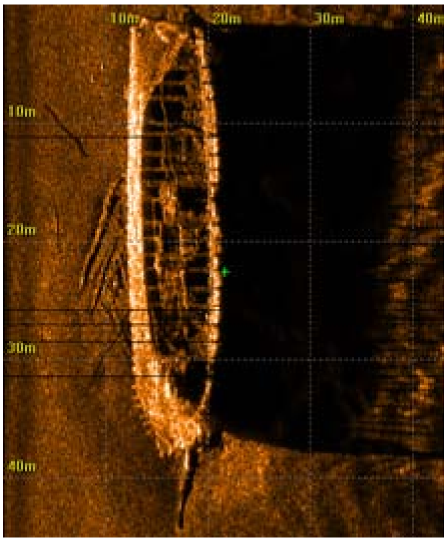


Figure 2 Side-scan sonar image of shipwreck "Aid" in Estonia

Technology

High-frequency sidescan sonar is routinely used in qualitative seabed mapping studies where the primary aim is to locate features and objects on the seabed. The success of the method is largely due to the fact that it provides rapid coverage over the ground using instruments that are widely available, affordable and relatively easy to operate from a range of different vessels. In these studies, the data are presented as black and white "sonic photographs" which are interpreted by eye. Data processing is generally restricted to geometric corrections required to geographically position the pixels and image enhancement—effectively to make the image "look good" by balancing backscatter intensity levels (Johnson and Helferty, 1990). The method works best for surveys where distinct seabed features (such as lava flows and faults) display characteristic backscatter responses. The visual interpretation of the sidescan images is generally guided by additional "ground truthing" of the seabed which may take the form of grab samples, cores or underwater photographs (Blondel and Murton, 1997). Advanced interpretation uses textural analysis techniques to more rigorously discriminate between defined seabed classes (e.g., Pace and Gao, 1988; Huvenne et al., 2002). A disadvantage with this type of approach is that in many situations, there is a gradual change in seabed type, without clear demarcations between backscatter behaviour. One of the goals of the current research, therefore, is to extend the quantitative interpretation of sidescan data to enable the direct extraction of specific seafloor properties such as mean grain size, sediment sorting, lithology, grain shape or porosity. These geotechnical parameters are particularly important for marine construction and environmental studies in shallow water.

Seabed acoustic imagery may contain (i) specular (true) reflections and acoustic shadows generated at the seabed as well as (ii) backscatter from seabed irregularities (surface scattering) or from heterogeneities within the near-surface sediments (volume reverberation, Urick, 1967). A major obstacle to interpreting the imagery is that the physics of scattering is complex and not fully understood (Jackson et al., 2002). It has even proven problematic to numerically model the measured backscatter response of well - characterized sediments made under highly controlled field conditions (Williams et al., 2002). However, it is known that the backscattering phenomena are related to seabed roughness or volumetric heterogeneity on scales similar to that of the incident wavelength and have a grazing angle dependence (Gardner et al., 1991; Jackson et al., 1986). Surface roughness or internal heterogeneity may be directly related to grain size or other factors such as sedimentary structures, bioturbation or gas bubbles (Urgeles et al., 2002; Fonseca et al., 2002). For real seabeds, the situation is further complicated if bedforms such as ripples change the local grazing angle and so cause an azimuthal dependence on the surface backscatter (Bell et al., 1999). For volume scattering, the backscatter intensity level is also influenced by the depth of penetration of the signal, which is a function of acoustic attenuation of the sediment and the acoustic frequency (Stanton, 1984; Jackson et al., 1986). In theory, volume scattering should not occur beyond the critical angle (total internal reflection occurs), but in practice, significant returns have been recorded at these larger angles (Jackson et al., 2002).

Recently, there has been some success in the development of commercial seabed classification systems using conventional single beam, vertical incidence echo-sounders (collectively known as dAcoustic Ground Discrimination SystemsT, AGDS). One such system, RoxAnnk (Stenmar Microsystems, Aberdeen) uses analogue signal processing hardware to extract two indices from the echo return (Burns et al., 1985; Chivers et al., 1990)—the envelope of the decaying return after the initial peak, termed E1, and the entire first multiple reflection, E2 (Fig. 3). The first and last point in each of the integrals is calculated automatically by a logic control circuitry. A rougher surface is expected to have a lower initial peak and a longer tail than a smoother surface of the same composition (acoustic impedance), hence, E1 is sometimes known as b roughnessQ (Hamilton et al., 1999). Similarly, a hard seabed (high acoustic impedance) reflects a greater proportion of the incident energy making the second echo stronger than a soft seabed, hence, E2 is sometimes known as bhardnessQ. During surveying, E1 and E2 are displayed on a Cartesian XY plot, and different regions on the graph assigned to user-defined seabed classes. Despite the ad hoc method of classification, the system represents a step-forward in the automatic classification of seabed type and has the advantage that it can be conducted in real time by a range of operators. Accuracy in the seabed classification (when compared to ground truth results) as high as 80% has been reported (e.g., Pinn and Robertson, 2003). The raw data can also be exported for post processing and more sophisticated image classification using supervised and unsupervised classification techniques (e.g., Sotheran et al., 1997; Greenstreet et al., 1997; Foster-Smith and Sotheran, 2003). The largest technical problem with RoxAnn appears to be in the measurement of the second echo strength, E2. Previous studies have reported correlations between E2 and ship speed, presumably due to a significant reduction in the reflection coefficient of the sea-surface around the vessel as it travels faster (Schlagentweit, 1993; Hamilton et al., 1999).

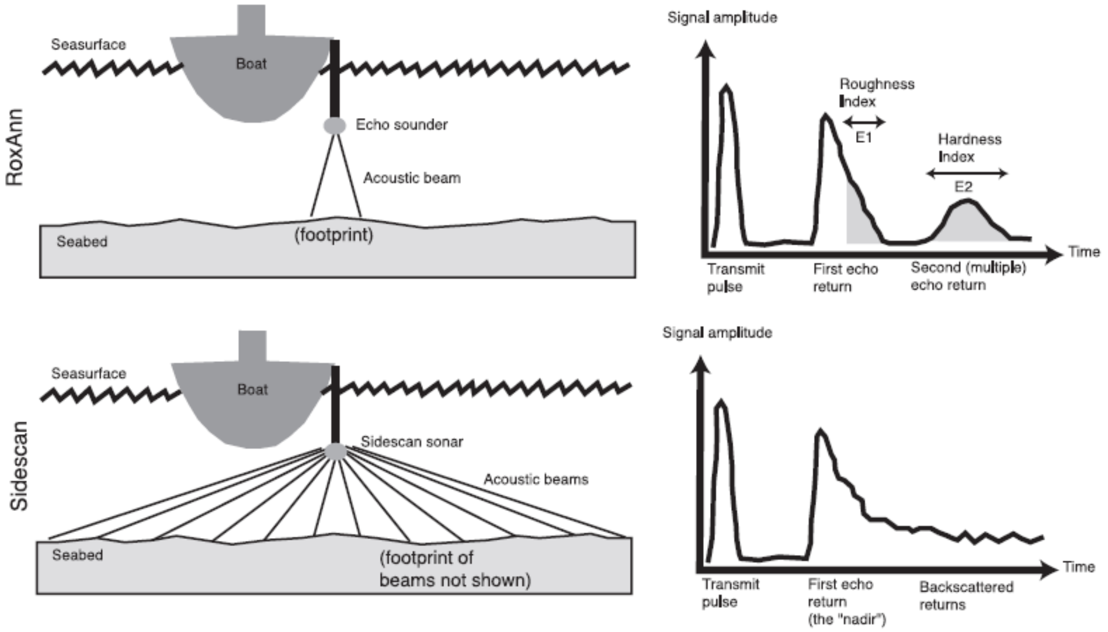


Figure 3 Cartoon showing the different acquisition geometries and signal records of RoxAnn and sidescan.

Sidescan sonar operates by emitting a fan or swathe of acoustic energy (Fig. 3). Data are therefore collected over a wide range of grazing angles, with a single grazing angle measurement at any point on the seabed. Therefore, although the method has a great advantage over single beam methods that data is collected from most of the seabed (without the need to interpolate between tracks) and the acoustic footprint on the seabed is generally much smaller, it has the disadvantage that the measurements are not made with the same insonification geometry (Hughes-Clarke, 1994). In this study, we attempt to correct for the grazing-angle dependence on backscatter by empirically estimating it from field data and removing it. This requires us to assume that the acoustic properties of the seabed sediments within our small study area do not vary significantly. We use a field dataset typical of a midbudget site investigation, collected with a commercial dual frequency sidescan fish. Our dataset has a number of limitations, and is subject to the usual problem of water column noise associated with towed instruments. We assess the success of our analysis by comparing the processed sidescan backscatter data to sediment grain size distributions from ground truth samples. In addition, we compare the sidescan results against those obtained from a normal-incidence RoxAnn study. In the mainstream literature, there are few examples comparing sidescan and RoxAnn surveys (Collins and Voulgaris, 1993, being an exception). The overall aim of our work was to assess the potential of sidescan for automatic ground discrimination. The method has several advantages over single-beam work in terms of spatial coverage and resolution, yet, it needs to be demonstrated that robust quantitative results can be extracted.

2.5 Remotely Operated Vehicle

A **remotely operated underwater vehicle** (**ROV**) is a tethered underwater mobile device. This meaning is different from remote control vehicles operating on land or in the air. ROVs are unoccupied, highly maneuverable, and operated by a crew aboard a vessel. They are common in deep water industries such as offshore hydrocarbon extraction. They are linked to a host ship by a neutrally buoyant tether or, often when working in rough conditions or in deeper water, a load-carrying umbilical cable is used along with a tether management system (TMS). The TMS is either a garage-like device which contains the ROV during lowering through the splash zone or, on larger work-class ROVs, a separate assembly which sits on top of the ROV. The purpose of the TMS is to lengthen and shorten the tether so the effect of cable drag where there are underwater currents is minimized. The umbilical cable is an armored cable that contains a group of electrical conductors and fiber optics that carry electric power, video, and data signals between the operator and the TMS. Where used, the TMS then relays the signals and power for the ROV down the tether cable. Once at the ROV, the electric power is distributed between the components of the ROV. However, in high-power applications, most of the electric power drives a high-power electric motor which drives a hydraulic pump. The pump is then used for propulsion and to power equipment such as torque tools and manipulator arms where electric motors would be too difficult to implement subsea. Most ROVs are equipped with at least a video camera and lights. Additional equipment is commonly added to expand the vehicle's capabilities. These may include sonars, magnetometers, a still camera, a manipulator or cutting arm, water samplers, and instruments that measure water clarity, water temperature, water density, sound velocity, light penetration, and temperature.

History

In the 1970s and '80s the Royal Navy used "Cutlet", a remotely operated submersible, to recover practice torpedoes and mines. RCA (Noise) maintained the "Cutlet 02" System based at BUTEC ranges, whilst the "03" system was based at the submarine base on the Clyde and was operated and maintained by RN personnel.

Figure 4 A Royal Navy ROV (*Cutlet*) first used in the 1950s to retrieve practice torpedoes and mines

The U.S. Navy funded most of the early ROV technology development in the 1960s into what was then named a "Cable-Controlled Underwater Recovery Vehicle" (CURV). This created the capability to perform deep-sea rescue operation and recover objects from the ocean floor, such as a nuclear bomb lost in the Mediterranean Sea after the 1966 Palomares B-52 crash. Building on this technology base; the offshore oil & gas industry created the work-class ROVs to assist in the development of offshore oil fields. More than a decade after they were first introduced, ROVs became essential in the 1980s when much of the new offshore development exceeded the reach of human divers. During the mid-1980s the marine ROV industry suffered from serious stagnation in technological development caused in part by a drop in the price of oil and a global economic recession. Since then, technological development in the ROV industry has accelerated and today ROVs perform numerous tasks in many fields. Their tasks range from simple inspection of subsea structures, pipelines, and platforms, to connecting pipelines and placing underwater manifolds. They are used extensively both in the initial construction of a sub-sea development and the subsequent repair and maintenance.

Submersible ROVs have been used to locate many historic shipwrecks, including the RMS *Titanic*, the *Bismarck*, USS *Yorktown*, and SS *Central America*. In some cases, such as the *Titanic* and the *SS Central America*, ROVs have been used to recover material from the sea floor and bring it to the surface.

While the oil and gas industry uses the majority of ROVs, other applications include science, military, and salvage. The military uses ROV for tasks such as mine clearing and inspection. Science usage is discussed below.

Construction

Work-class ROVs are built with a large flotation pack on top of an aluminium chassis to provide the necessary buoyancy to perform a variety of tasks. The sophistication of construction of the aluminum frame varies depending on the manufacturer's design. Syntactic foam is often used for the flotation material. A tooling skid may be fitted at the bottom of the system to accommodate a variety of sensors or tooling packages. By placing the light components on the top and the heavy components on the bottom, the overall system has a large separation between the center of buoyancy and the center of gravity: this provides stability and the stiffness to do work underwater. Thrusters are placed between center of buoyancy and center of gravity to maintain the attitude stability of the robot in maneuvers. Various thruster configurations and control algorithms can be used to give appropriate positional and attitude control during the operations, particularly in high current waters. Thrusters are usually in a balanced vector configuration to provide the most precise control possible.

Electrical components can be in oil-filled water tight compartments or one-atmosphere compartments to protect them from corrosion in seawater and being crushed by the extreme pressure exerted on the ROV while working deep. The ROV will be fitted with cameras, lights and manipulators to perform basic work. Additional sensors and tools can be fitted as needed for specific tasks. It is common to find ROVs with two robotic arms; each manipulator may have a different gripping jaw. The cameras may also be guarded for protection against collisions. An ROV may be equipped with Sonar and LiDAR equipment.

The majority of the work-class ROVs are built as described above; however, this is not the only style in ROV building method. Smaller ROVs can have very different designs, each appropriate to its intended task. Larger ROVs are commonly deployed and operated from vessels, so the ROV may have landing skids for retrieval to the deck.

Configurations

Remotely operated vehicles have three basic configurations. Each of these brings specific limitations.

- **Open or Box Frame ROVs** - this is the most familiar of the ROV configurations - consisting of an open frame where all the operational sensors, thrusters, and mechanical components are enclosed. These are useful for free-swimming in light currents (less than 4 knots based upon manufacturer specifications). These are not suitable for towed applications due to their very poor hydrodynamic design. Most Work-Class and Heavy Work-Class ROVs are based upon this configuration.
- **Torpedo Shaped ROVs** - this is a common configuration for data gathering or inspection class ROVs. The torpedo shape offers low hydrodynamic resistance, but comes with significant control limitations. The torpedo shape requires high speed (which is why this shape is used for military munitions) to remain positionally and attitudinally stable, but this type is highly vulnerable at high speed. At slow speeds (0-4 knots) suffers from numerous instabilities, such as tether induced roll and pitch, current induced roll, pitch, and yaw. It has limited control surfaces at the tail or stern, which easily cause over compensation instabilities. These are frequently referred to as "Tow Fish", since they are more often used as a towed ROV.

Survey use

Survey or Inspection ROVs are generally smaller than workclass ROVs and are often sub-classified as either Class I: Observation Only or Class II Observation with payload. They are used to assist with hydrographic survey, ie the location and positioning of subsea structures, and also for inspection work for example pipeline surveys, jacket inspections and marine hull inspection of vessels. Survey ROVs also known as "eyeballs" although smaller than workclass often have comparable performance with regard to the ability to hold position in currents, and often carry similar tools and equipment - lighting, cameras, sonar, USBL (Ultra-short baseline) beacon, and strobe flasher depending on the payload capability of the vehicle and the needs of the user. Some class II ROVs are also equipped with smaller manipulator units either pole based or included within a tooling skid. Their use is slowing growing in popularity as industry looks for safer alternatives to using divers.

Military use

ROVs have been used by several navies for decades, primarily for minehunting and minebreaking.

In October 2008 the U.S. Navy began to replace its manned rescue systems, based on the Mystic DSRV and support craft, with a modular system, the SRDRS based on a tethered, unmanned ROV called a pressurized rescue module (PRM). This followed years of tests and exercises with submarines from the fleets of several nations.

The US Navy also uses an ROV called AN/SLQ-48 Mine Neutralization Vehicle (MNV) for mine warfare. It can go 1000 yards away from the ship due to a connecting cable, and can reach 2000 feet deep. The mission packages available for the MNV are known as MP1, MP2, and MP3.

- The MP1 is a cable cutter to surface the moored mine for recovery exploitation or Explosive Ordnance Disposal (EOD).
- The MP2 is a bomblet of 75 lb polymer-bonded explosive PBXN-103 high explosive for neutralizing bottom/ground mines.
- The MP3 is a moored mine cable gripper and a float with the MP2 bomblet combination to neutralize moored mines underwater.

The charges are detonated by acoustic signal from the ship.
The AN/BLQ-11 autonomous Unmanned Undersea Vehicle (UUV) is designed for covert mine countermeasure capability and can be launched from certain submarines.

The U.S.Navy's ROVs are only on Avenger-class mine countermeasures ships. After the grounding of USS *Guardian* (MCM-5) and decommissioning of USS *Avenger* (MCM-1), and USS *Defender* (MCM-2), only 11 US Minesweepers remain operating in the coastal waters of Bahrain (USS *Sentry* (MCM-3), USS *Devastator* (MCM-6), USS *Gladiator* (MCM-11) and USS *Dextrous* (MCM-13)), Japan (USS *Patriot* (MCM-7), USS *Pioneer* (MCM-9), USS *Warrior* (MCM-10) and USS *Chief* (MCM-14)), and California (USS *Champion* (MCM-4), USS *Scout* (MCM-8), and USS *Ardent* (MCM-12)).

During August 19, 2011, a Boeing-made robotic submarine dubbed Echo Ranger was being tested for possible use by the U.S. military to stalk enemy waters, patrol local harbors for national security threats and scour ocean floors to detect environmental hazards.

As their abilities grow, smaller ROVs are also increasingly being adopted by navies, coast guards, and port authorities around the globe, including the U.S. Coast Guard and U.S. Navy, Royal Netherlands Navy, the Norwegian Navy, the Royal Navy and the Saudi Border Guard. They have also been widely adopted by police departments and search and recovery teams. Useful for a variety of underwater inspection tasks such as explosive ordnance disposal (EOD), meteorology, port security, mine countermeasures (MCM), and maritime intelligence, surveillance, reconnaissance (ISR).

Science use

Figure 5 ROV Max Rover Hellenic Center of Marine Research

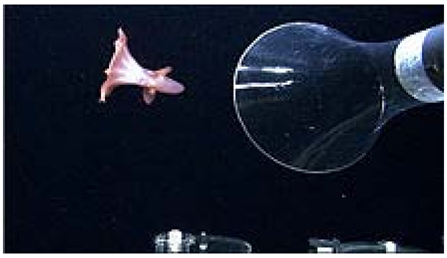


Figure 6 A ROV's suction device about to capture a specimen of the deep sea octopus

ROVs are also used extensively by the scientific community to study the ocean. A number of deep sea animals and plants have been discovered or studied in their natural environment through the use of ROVs: examples include the jellyfish *Stellamedusa ventana* and the eel-like halosaurs. In the USA, cutting edge work is done at several public and private oceanographic institutions, including the Monterey Bay Aquarium Research Institute (MBARI), the Woods Hole Oceanographic Institution (WHOI) (with *Nereus*), and the University of Rhode Island / Institute for Exploration (URI/IFE). The picture to the right shows the behavior and microdistribution of krill under the ice of Antarctica.

Science ROVs take many shapes and sizes. Since good video footage is a core component of most deep-sea scientific research, research ROVs tend to be outfitted with high-output lighting systems and broadcast quality cameras.[16] Depending on the research being conducted, a science ROV will be equipped with various sampling devices and sensors. Many of these devices are one-of-a-kind, state-of-the-art experimental components that have been configured to work in the extreme environment of the deep ocean. Science ROVs also incorporate a good deal of technology that has been developed for the commercial ROV sector, such as hydraulic manipulators and highly accurate subsea navigation systems. They are also used for underwater archaeology projects such as the *Mardi Gras* Shipwreck Project in the Gulf of Mexico.

While there are many interesting and unique science ROVs, there are a few larger high-end systems that are worth taking a look at. MBARI's *Tiburon* vehicle cost over $6 million US dollars to develop and is used primarily for midwater and hydrothermal research on the West Coast of the US.[19] WHOI's *Jason* system has made many significant contributions to deep-sea oceanographic research and continues to work all over the globe. URI/IFE's *Hercules* ROV is one of the first science ROVs to fully incorporate a hydraulic propulsion system and is uniquely outfitted to survey and excavate ancient and modern shipwrecks. The Canadian Scientific Submersible Facility *ROPOS* system is continually used by several leading ocean sciences institutions and universities for challenging tasks such as deep-sea vents recovery and exploration to the maintenance and deployment of ocean observatories.

Educational outreach

The *SeaPerch* Remotely Operated Underwater Vehicle (ROV) educational program is an educational tool and kit that allows elementary, middle, and high-school students to construct a simple, remotely operated underwater vehicle, from polyvinyl chloride (PVC) pipe and other readily made materials. The SeaPerch program teaches students basic skills in ship and submarine design and encourages students to explore naval architecture and marine and ocean engineering concepts. *SeaPerch* is sponsored by the Office of Naval Research, as part of the National Naval Responsibility for Naval Engineering (NNRNE), and the program is managed by the Society of Naval Architects and Marine Engineers.

Another innovative use of ROV technology was during the *Mardi Gras* Shipwreck Project. The "Mardi Gras Shipwreck" sank some 200 years ago about 35 miles off the coast of Louisiana in the Gulf of Mexico in 4,000 feet (1220 meters) of water. The shipwreck, whose real identity remains a mystery, lay forgotten at the bottom of the sea until it was discovered in 2002 by an oilfield inspection crew working for the Okeanos Gas Gathering Company (OGGC). In May 2007, an expedition, led by Texas A&M University and funded by OGGC under an agreement with the Minerals Management Service (now BOEM), was launched to undertake the deepest scientific archaeological excavation ever attempted at that time to study the site on the seafloor and recover artifacts for eventual public display in the Louisiana State Museum. As part of the educational outreach Nautilus Productions in partnership with BOEM, Texas A&M University, the Florida Public Archaeology Network and Veolia Environmental produced a one-hour HD documentary about the project, short videos for public viewing and provided video updates during the expedition. Video footage from the ROV was an integral part of this outreach and used extensively in the *Mystery Mardi Gras Shipwreck* documentary.

The Marine Advanced Technology Education (MATE) Center uses ROVs to teach middle school, high school, community college, and university students about ocean-related careers and help them improve their science, technology, engineering, and math skills. MATE's annual student ROV competition challenges student teams from all over the world to compete with ROVs that they design and build. The competition uses realistic ROV-based missions that simulate a high-performance workplace environment, focusing on a different theme that exposes students to many different aspects of marine-related technical skills and occupations. The ROV competition is organized by MATE and the Marine Technology Society's ROV Committee and funded by organizations such as the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and Oceaneering, and many other organizations that recognize the value of highly trained students with technology skills such as ROV designing, engineering, and piloting. MATE was established with funding from the National Science Foundation and is headquartered at Monterey Peninsula College in Monterey, California.

Broadcast use

As cameras and sensors have evolved and vehicles have become more agile and simple-to-pilot ROVs have become popular particularly with documentary filmmakers due to their ability to access deep, dangerous, and confined areas unattainable by divers. There is no limit to how long an ROV can be submerged and capturing footage which allows for previously unseen perspectives to be gained. ROVs have been used in the filming of several documentaries including Nat Geo's Shark Men and The Dark Secrets of the Lusitania and the BBC Wildlife Special Spy in the Huddle.

Due to their extensive use by military, law enforcement, and coastguard services, ROVs have also featured in crime dramas such as popular CBS series CSI.

Classification

Submersible ROVs are normally classified into categories based on their size, weight, ability or power. Some common ratings are:

- Micro - typically Micro-class ROVs are very small in size and weight. Today's Micro-Class ROVs can weigh less than 3 kg. These ROVs are used as an alternative to a diver, specifically in places where a diver might not be able to physically enter such as a sewer, pipeline or small cavity.
- Mini - typically Mini-Class ROVs weigh in around 15 kg. Mini-Class ROVs are also used as a diver alternative. One person may be able to transport the complete ROV system out with them on a small boat, deploy it and complete the job without outside help. Some Micro and Mini classes are referred to as "eyeball"-class to differentiate them from ROVs that may be able to perform intervention tasks.
- General - typically less than 5 HP (propulsion); occasionally small three finger manipulators grippers have been installed, such as on the very early RCV 225. These ROVs may be able to carry a sonar unit and are usually used on light

survey applications. Typically the maximum working depth is less than 1,000 metres though one has been developed to go as deep as 7,000 m.

- Inspection Class - these are typically rugged commercial or industrial use observation and data gathering ROVs - typically equipped with live-feed video, still photography, sonar, and other data collection sensors. Inspection Class ROVs can also have manipulator arms for light work and object manipulation.
- Light Workclass - typically less than 50 hp (propulsion). These ROVs may be able to carry some manipulators. Their chassis may be made from polymers such as polyethylene rather than the conventional stainless steel or aluminium alloys. They typically have a maximum working depth less than 2000 m.
- Heavy Workclass - typically less than 220 hp (propulsion) with an ability to carry at least two manipulators. They have a working depth up to 3500 m.
- Trenching & Burial - typically more than 200 hp (propulsion) and not usually greater than 500 hp (while some do exceed that) with an ability to carry a cable laying sled and work at depths up to 6000 m in some cases.

Submersible ROVs may be "free swimming" where they operate neutrally buoyant on a tether from the launch ship or platform, or they may be "garaged" where they operate from a submersible "garage" or "tophat" on a tether attached to the heavy garage that is lowered from the ship or platform. Both techniques have their pros and cons; however very deep work is normally done with a garage.

CHAPTER 3

THE ORIGIN OF SUBMARINE CANYONS

3.1 The origins of submarine canyons

The origins of submarine canyons are attributed to multiple causes, but chief amongst these is erosion of the slope by mass wasting events (slumping and submarine landslides) and turbidity currents. Modelling of the formation and development of submarine canyons has revealed the importance of headward erosion driven by sediment flow down-cutting, in which tributaries are the precursors of larger submarine canyon systems. Thus canyons once formed by slumping evolve by further slumping, density flow erosion and subsequent capture of smaller adjacent canyons to form dendritic complexes.

The geomorphic attributes of canyons (catchment area and slope gradient) share interesting similarities with subaerial channels eroded by water runoff, which is explained in terms of turbidity currents and other sedimentary flows that originate from failure of over-steepened deposits in canyon walls. In this way the frequency of erosive flows experienced by the channel increases with canyon "catchment area", and includes, but is not restricted to, the hemipelagic "rain" of sediment falling within its submarine catchment. The major groups of processes that generate canyon-incising turbidity flows are transformation of failed sediment, hyperpycnal flow from rivers or ice margins, and resuspension of sediment near the shelf edge by oceanographic processes followed by down-slope transport as turbidity currents. These processes are of particular significance for canyons that incise the continental shelf edge thus connecting the canyon system to sediment sources on the shelf and adjacent terrestrial environments. Some canyons exhibit structural control where faulting and fracture of basement rock has been followed by erosion. Tectonism can also influence the course of some canyons, with the canyon thalweg being deflected along faults and structural features.

Blind canyons are wholly confined to the continental slope and are therefore isolated from shelf-originating, down-slope erosive flows. Additionally is attributed the origins of some blind canyons to fluid seepage-induced slope failure. Thus, once a slump scar forms, there is an increase in the head gradient of internal fluids that drives further failures such that the original slump scar is enlarged. Fluid escape along a section of continental slope prone to slump-failure will then theoretically produce a self-organised, regular pattern of alternating spurs and canyons. The regular spacing of blind canyons varies from as small a distance as 280 m (eg study site adjacent to the island of Hispaniola), to 8.85 km (eg on the Florida escarpment). More generally, once the initial canyon has formed, modelling of headward erosion and enlargement by slumping has been shown to explain the morphology of some canyon systems.

Subaerial erosion can be an important factor in canyon evolution. Most shelves were subaerially exposed at the peak of the last ice age when global eustatic sea level was ~120 m below its present position and rivers incised valleys across what is today the continental shelf. The delivery of sediments to the shelf break during Pleistocene sea level low stands provided a sediment source for down-slope turbidity flows and canyon incision, a process that occurs in only a few canyon systems during interglacial high sea level periods. Margin exposure has been especially significant in isolated marine basins such as the Mediterranean Sea, where extensive sea level lowering and desiccation occurred during the late Miocene “Messinian Salinity Crisis” and the Pleistocene evaporation of the Black Sea.

The relief of canyons may be accentuated by deposition of sediments and vertical growth along the canyon flanks, whereas deposition along the canyon floor is prevented by the effects of turbidity currents (gravity flows) and/or internal waves.

3.2 Evolution of submarine canyons

Two main hypotheses have been proposed to explain the origin and development of submarine canyons along continental margins and include:

1) river erosion and/or erosion under shallow-water conditions and

2) slope failure and retrogressive (headward) erosion

Namely:

1) River erosion and erosion under shallow-water conditions can occur in the upper reaches of submarine canyons when relict fluvial courses are active during sea-level falls and sea-level lowstands . Downward processes in shallow marine settings, including hyperpycnal (near bottom) flows, storm- and current-driven erosive flows , and other erosive flows (turbidity flows sensu lato) of different origin, lead to seaward excavation and entrenchment of submarine canyons across continental slope to the basin floor.

2) Slope failure and retrogressive erosion can occur on the continental slope at different depths, independently of sediment input and sealevel variation. Mass failure processes can be triggered by slope oversteepening, fluid and/or gas venting in the continental slope, tectonic deformation/faulting and earthquakes.

These mechanisms of canyon inception therefore condition the canyon morphology, although internal canyon variability and complexity may obscure the relationship between canyon morphologies and their genesis. Thus, shelf-indenting canyons (Type 1) are generally thought to be linked to river erosion and/or downward eroding sediment gravity flows, while the onset of slope-confined canyons (Type 2) is attributed to slope failure and upslope retrogressive erosion.

One major model for canyon formation is the model of Farre et al. (1983). This model consists of three phases, where down- and upslope processes interact to shape the submarine canyons.

Phase 1: initial or youthful stage. Pre-conditioning factors such as low sediment strength, differential compaction in the sediment, permeability, underconsolidation, or the presence of faults and other tectonic structures lead to localised slope failures (Fig. 7, phase 1a). Triggering factors could include fluid escapes, earthquakes and sediment overpressure by rapid deposition, and/or oversteepening. If conditions are favourable, upslope retreat of the failed surfaces by progressive sediment destabilisation and retrogressive erosion leads to the formation of an initial submarine canyon (Fig. 7, phase 1b). Additionally, erosive sediment flows derived from failed material could excavate axial incisions in the landslide scars that would contribute to the headward erosion of the canyon.

Phase 2: transitional stage. In this phase the initial canyons progress upslope to near the shelf-break (Fig. 7, phase 2). Canyon growth mechanisms are similar to phase 1.

Phase 3: mature stage. This phase involves a change in the erosion style of the canyons which may breach the shelf-edge (Fig. 7, phase 3) due to progressive upslope erosion. This stage is represented by shelf-incised submarine canyons (Type 1). The canyon heads act as catchment areas for shelf and river sediments that bypass the slope through the canyon valleys and are deposited on the basin floor. Submarine canyons become more active due to the increased sediment supply provided from different areas on the shelf. Downward sediment gravity flows can contribute significantly to ongoing canyon excavation and enlargement by axial incision and linked wall collapses. As a consequence, a network of downward connected gullies develops, forming an amphitheatre-like canyon head. Similarly at this stage, different canyon valleys may coalesce into a larger one, forming multi-fed, shelf-incised submarine canyons (Type 1b). Moreover, downslope and upslope processes can act together to maintain and enlarge these submarine canyons in their mature phase.

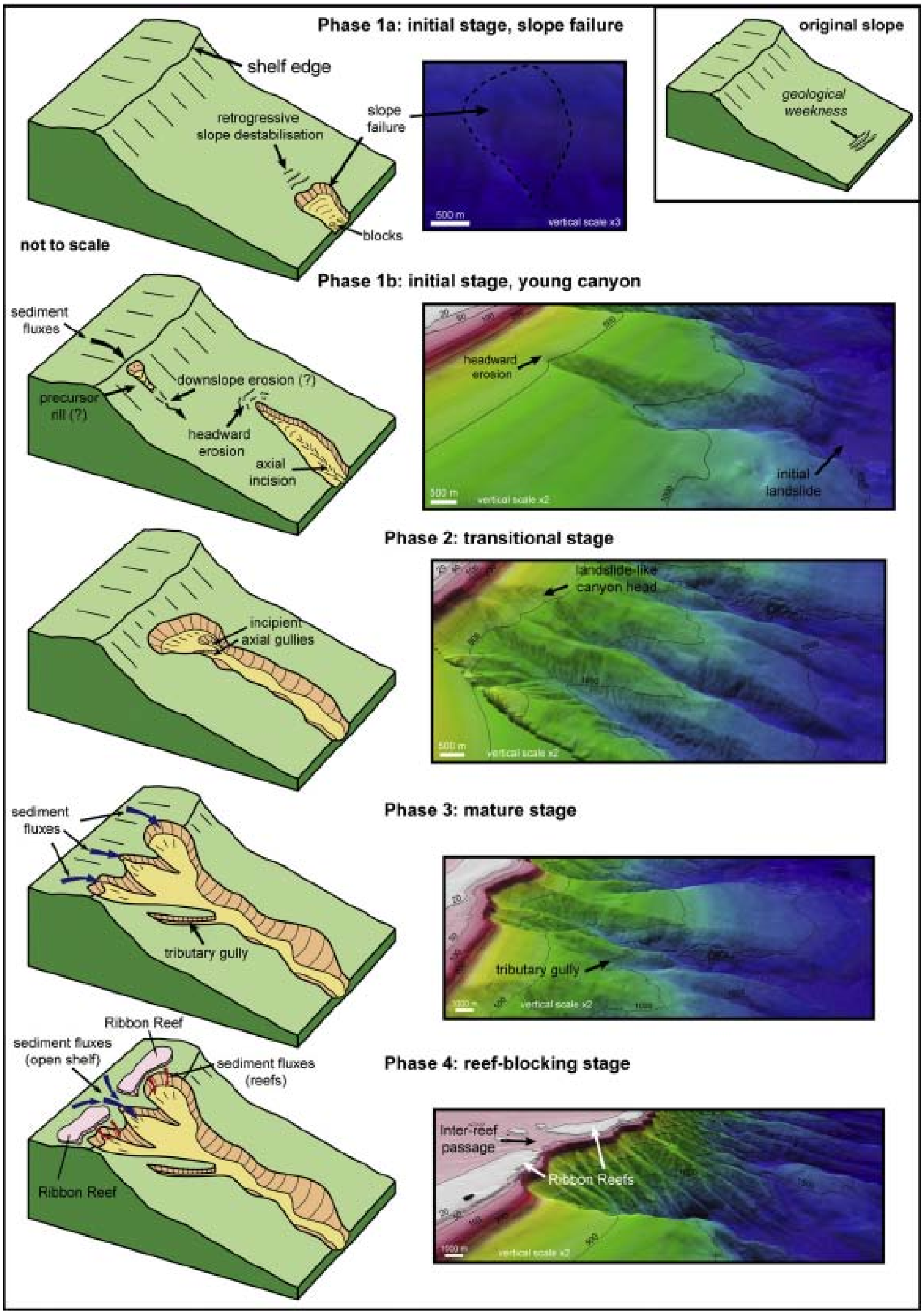


Figure 7 Canyon formation

Phase 4: reef-blocking stage. Whether fully, partially, or unblocked by reefs, the sediment supply into the canyons, and thus the type and frequency of eroding sediment gravity flows responsible of their excavation, is different.

3.3 Control parameters on canyon evolution

The proposed theoretical model of the evolution of the canyon, from initiation to infill, is characterised by the specific sedimentary processes and architectures summarised in Fig. 8. These include three main stages of evolution occurring at three different time periods: (1) initiation caused by intra-slope destabilisations, (2) up-slope migration by retrogressive erosion, and (3) canyon infill by periplatform ooze. Here, we address the potential control parameters for each of these three time periods.

(1) This dataset suggests that canyon initiation results from slope failures. Several submarine slides have been observed; these show numerous arcuate scarps on their steep edges, thus suggesting a continuum to canyon formation through retrogressive erosion processes. Large submarine slides often correspond to various triggering mechanisms. Slope failures could have been triggered by high sedimentation rates, the intensification of bottom currents or earthquakes. Moreover submarine landslides could therefore have been triggered by sediment overloading.

In addition to these triggering parameters, preconditioning factors could also favour slope failures. Indeed, submarine landslides could be linked to the presence of cemented surfaces generated by early diagenesis, which typically occurs during lowstand periods. These well-lithified surfaces could form a preferential detachment horizon and a gliding plane for the sliding sediments.

(2) The up-slope migration by retrogressive erosion includes two conceptual steps that control the morphological contrasts between the amphitheatre shapes at water depths ranging from 650 m to 800 m and the linear V-shaped incisions at water depths ranging from 450 m to 600 m. These two backstepping stages could be diachronous or coeval to the initiation of the canyon due to slope failures. In this case study, it is not possible to determine the relative timing of these steps.

The triggering mechanisms of such retrogressive erosions have been attributed to downslope eroding gravity flows, however, it remains difficult to distinguish between gravity-driven intra-slope erosion and downslope erosion caused by gravity flows that were initiated from the platform edge during canyon formation. That said, in this purely carbonate setting, it seems unlikely that gravity flows generated at the platform edge would have had sufficient intensity to cause seaward excavation.

(3) Under the current highstand shedding settings, carbonate production on the platform is believed to be maximal and the intensity of platform-derived sediment fluxes is expected to increase moving towards deep sea environments. However, the transfer of periplatform ooze is not uniform along the slope, i.e., significant

alongshore variability must be considered when dealing with platform-basin sediment transfer. Periplatform ooze is believed to be transported by either density cascading or muddy gravity flows confined within canyons. Present sea level highstand conditions have led to the flooding of the platform (between 3 and 8 m) but remains lesser than that recorded during earlier interglacials. During this latter extreme highstand, the complete flooding of the platform generated the full activity of the carbonate factory and increased carbonate production and off-bank transport. The presence of confined turbidite levees suggests that muddy flows may play an important role in canyon differentiation during the filling stages. The intensification of canyon infill may be linked to the development of preferential transfer axes for muddy gravity flows, particularly when the sea level is higher than the present sea level.

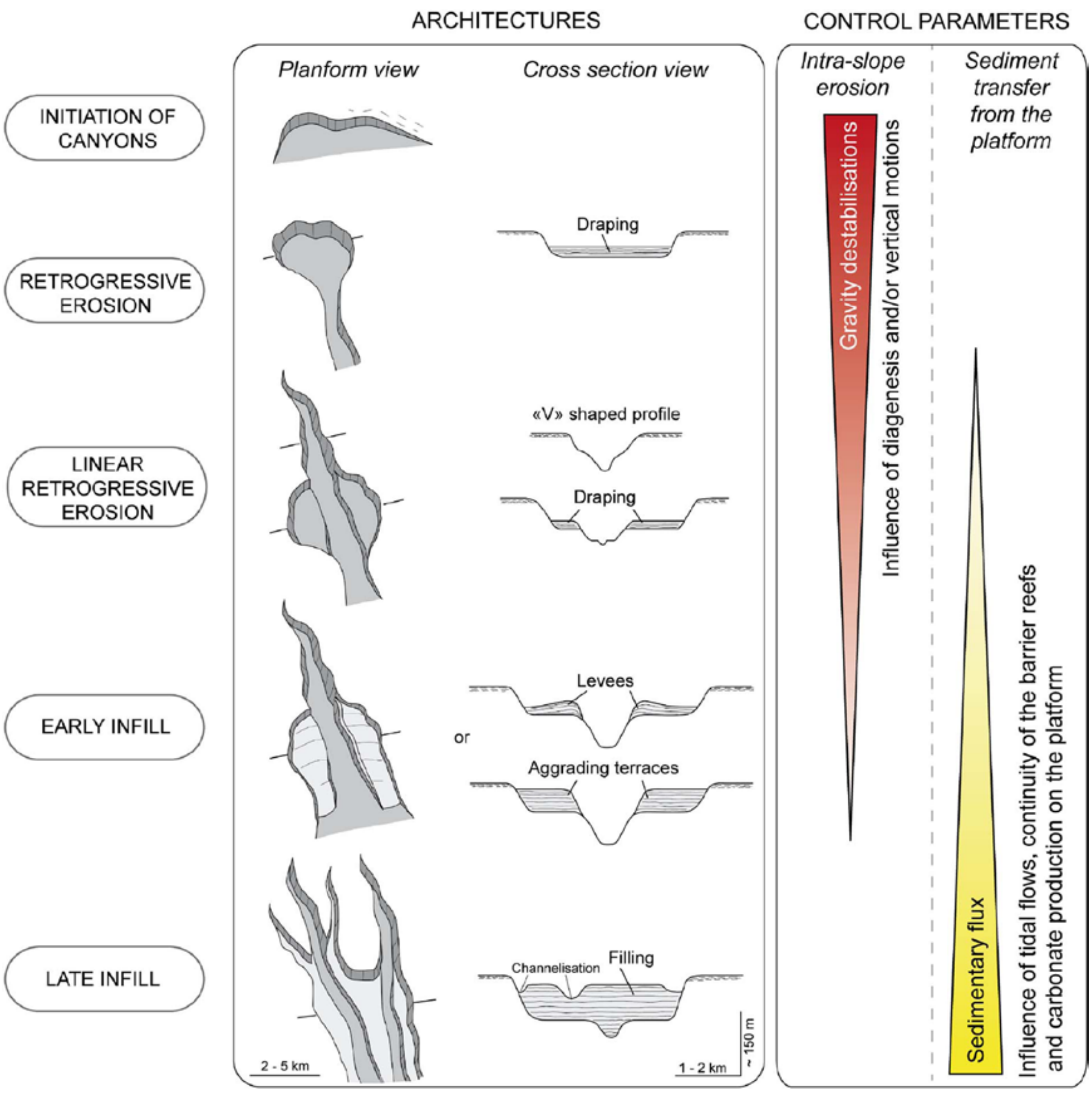


Figure 8 Summary diagram illustrating the platform morphologies and associated architectural styles of canyons relative to their main control parameters

3.4 Submarine canyon morphology

Submarine canyons are generally composed of three sections:

1) a canyon head, cutting the upper part of the slope or incising the shelf edge
2) a middle canyon, generally incising the continental slope, with or without tributary branches and
3) a canyon mouth debouching at abyssal depths often into basin areas.

The heads of some submarine canyons terminate on the slope, making socalled "blind" or "headless" canyons. The largest canyons, however, commonly incise into the continental shelf and may even continue as shelf valleys that have a direct connection to modern terrestrial fluvial systems. Analysing canyon morphometry can reveal important information concerning their evolution and relative maturity. Canyon thalwegs can be rectilinear or sinuous, and the long profile can be concave or convex in shape, with steps or knick points. The mean depth of canyon incision in Mediterranean canyons is about 1,600 m, which is small compared with global averages.

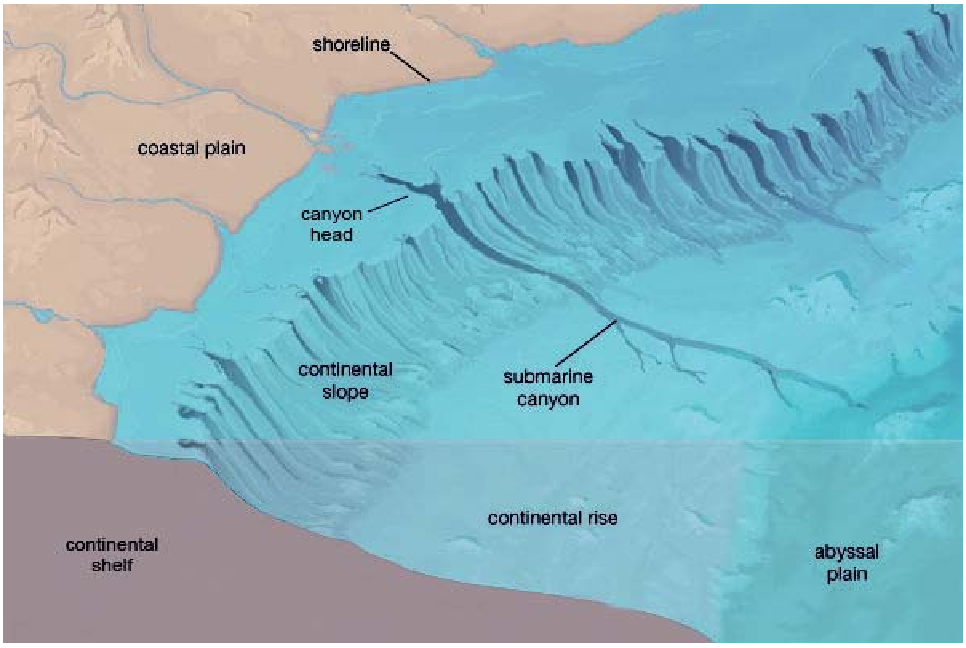


Figure 9 Schematic presentation of a submarine canyon

3.5 Continental margin type

Continental margins are divided in two basic types based on the process which associated with their formation. On the one hand there are the **active** (endogenetic) witch morphology is controlled by tectonic/magmatic processes (islands located on oceanic crust are thus included in the category of active tectonic environments, although they do not form part continental margins). On the other the **passive** (exogenetic) margins are controlled by erosion and deposition processes. As a result of the above separation, canyon's morphology vary between different types of margins, especially when tectonic events happen.

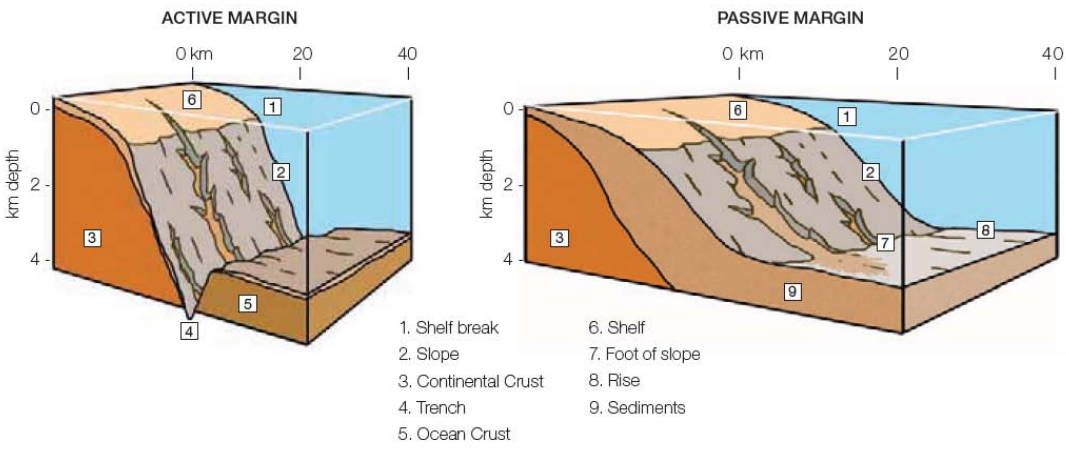


Figure 10 Margin types

Moreover, canyon's spacing, which are developing on passive margins, are associated positively with the slope of margin (for example on the Atlantic margin of the eastern United States) and with the strength of the material comprising the margin (weaker material acts in the same way as an increase in slope), leading to a closer spacing of canyons.

Further progress in classification of canyons was managed throw the study «Global distribution of large submarine canyons: Geomorphic differences between active and passive continental margins» (2011) of Peter T. Harris, Tanya Whiteway. The aim of this study is to assess the global occurrence of large submarine canyons to provide context and guidance for discussions regarding canyon occurrence, distribution, geological and oceanographic significance and conservation. Based on an analysis of the ETOPO1 data set, this study has compiled the first inventory of 5849 separate large submarine canyons in the world ocean. Active continental margins contain 15% more canyons (2586, equal to 44.2% of all canyons) than passive margins (2244, equal to 38.4%) and the canyons are steeper, shorter, more dendritic and more closely spaced on active than on passive continental margins. This study confirms observations of earlier workers that a relationship exists between canyon slope and canyon spacing (increased canyon slope correlates with closer canyon spacing). The greatest canyon spacing occurs in the Arctic and the Antarctic whereas canyons are more closely spaced in the Mediterranean than in other areas.

This study is based on an interpretation of the ETOPO1 bathymetric grid . This dataset is a 1 arc-minute (1 nautical mile=1.852 km) global relief model with bathymetry derived from sea-surface satellite altimetry measurements and ocean soundings provided by numerous sources. ETOPO1 thus includes existing bathymetry data and uses interpolated gravity values elsewhere. It incorporates regional bathymetry datasets from the Mediterranean Science Commission, United States Coastal Relief Model covering the east and west coasts, Gulf of Mexico, Hawaii and Puerto Rico, bathymetric grids of the seafloor surrounding Japan from the Japan Oceanographic Data Center, the International Bathymetric Chart of the Arctic Ocean and a grid of multibeam swath sonar bathymetric surveys from the Gulf of California. To assist in the identification of canyons, bathymetric data were contoured at 100 m intervals using ESRI's ArcGIS 9.3. The hydrologic analysis process in ArcGIS was applied to build drainage paths where at least 20 cells flowed into the one location (note that the grid was not smoothed prior to use, but was filled for major holes prior to stream path analysis). The final canyon map includes a combination of ArcGIS built, and manually drawn canyons where the built canyons were unclear. In this study, the size of canyons that could be mapped is constrained by the cell size of the bathymetry grid (1.852 km) and the subsequent contouring algorithm, which smoothes the output contours. Canyons were defined in this study purely on their morphology and in order to assure consistency in the identification and mapping of canyons, the following criteria were applied:

1. Canyon features had to span a minimum of 1000 m depth range— canyon features that did not extend over at least 1000 m were excluded.
2. The width/depth ratio (incision) of the canyon must be less than 150:1 and canyon incision had to exceed 100 m—features incised less than 100 m were excluded. Thus to be included, 100 m contours must deflect landward by at least 15 km and be spaced less than 15 km apart.
3. Canyons having heads that occur deeper than 4000 m were excluded.
4. Only canyons located on continental margins, the slopes of oceanic islands or submarine plateaus were included. Plateaus were required to reach a depth of less than 200 m at some point on their summit to be included. Canyons that incise the flanks of mid-ocean ridges, seamounts or other abyssal mountains were excluded.

Canyons that met the above four criteria were sub-divided into three main types:

Type 1
Shelf-incising canyons having heads with a clear bathymetric connection to a major river system

Type 2
Shelf-incising canyons with no clear bathymetric connection to a major river system

Type 3
Blind canyons incised onto the continental slope

All three canyon types include at least one major canyon thalweg (a) with possible tributary canyons (b, c, d and e) forming dendritic canyon complexes (Fig. 11).

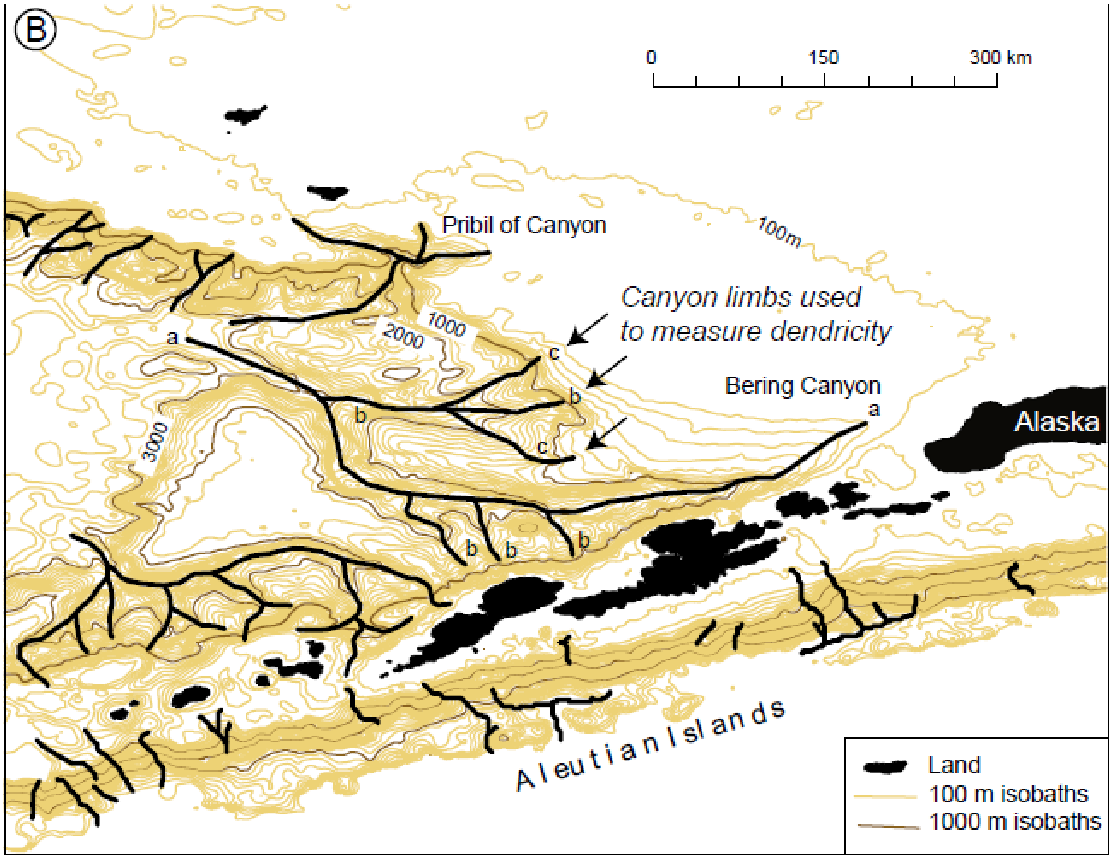


Figure 11 Diagram explaining how canyons are interpreted from contoured bathymetry data

To the following maps are shown the location of various canyons.

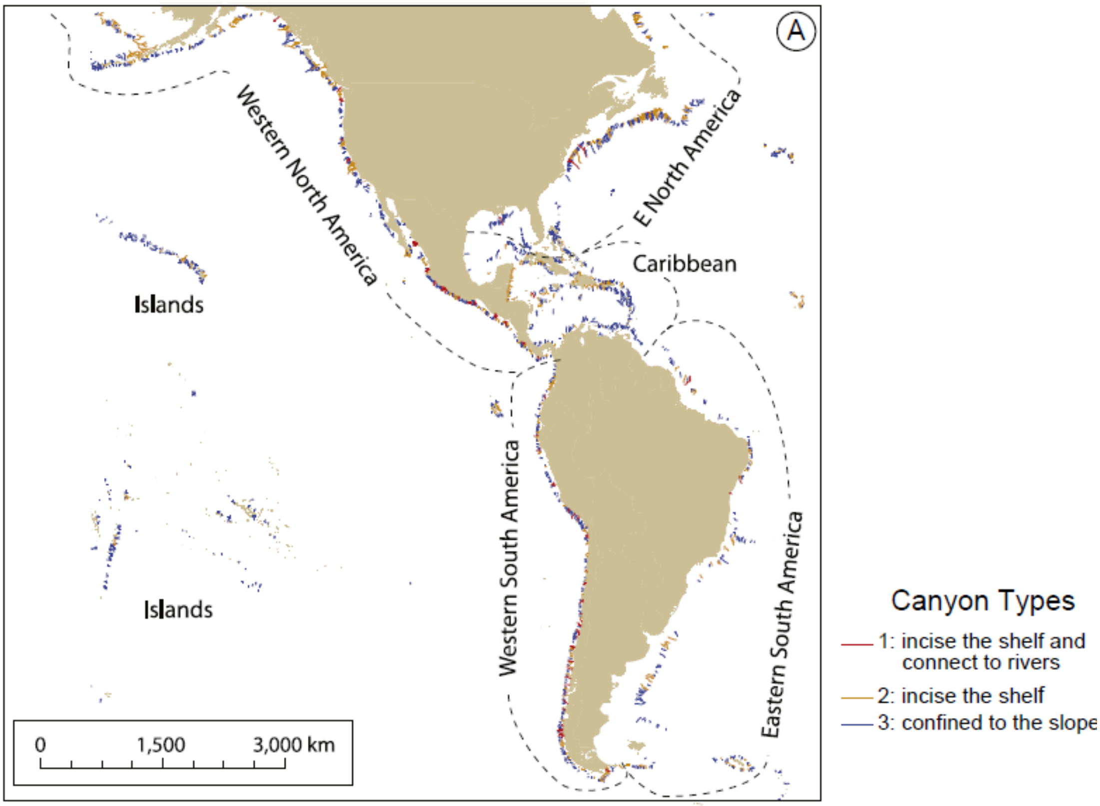


Figure 12 Canyons at East Pacific and West Atlantic ocean

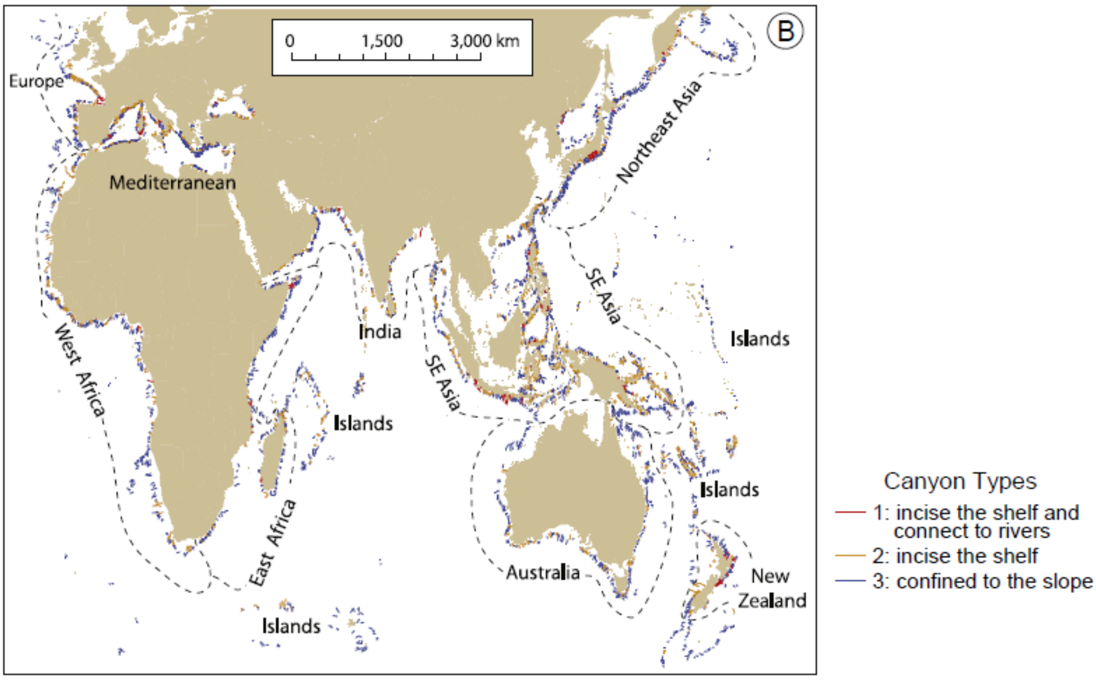


Figure 13 Canyons at East Atlantic, Indian and West Pacific ocean

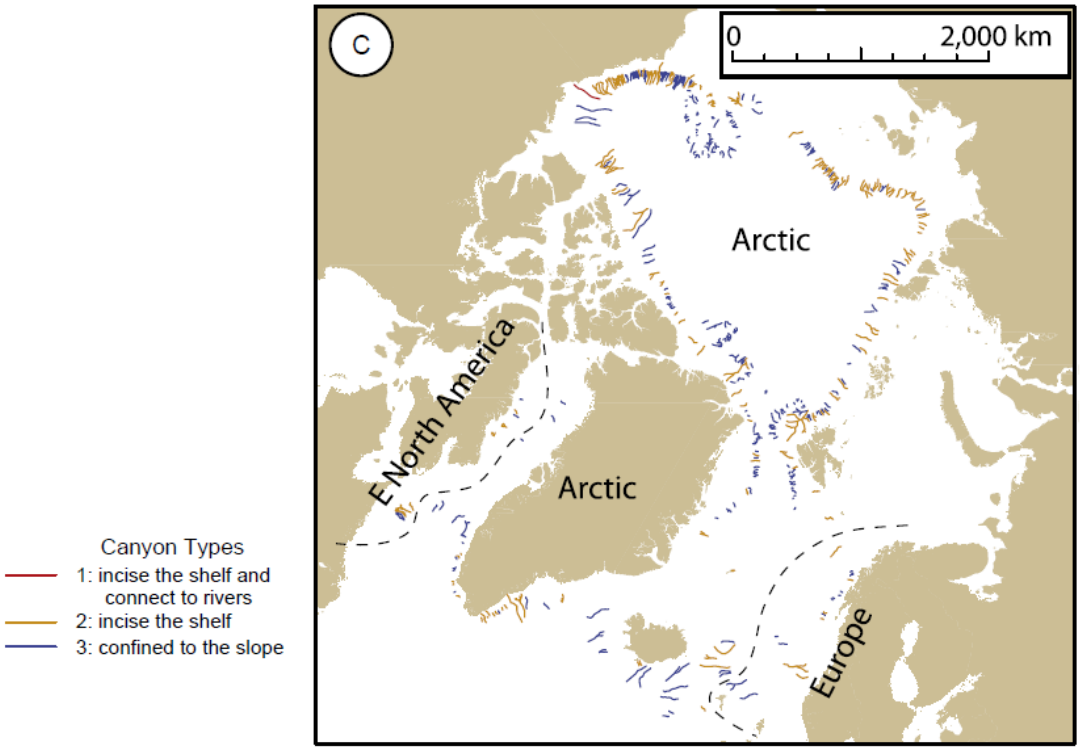


Figure 14 Canyons at Arctic ocean

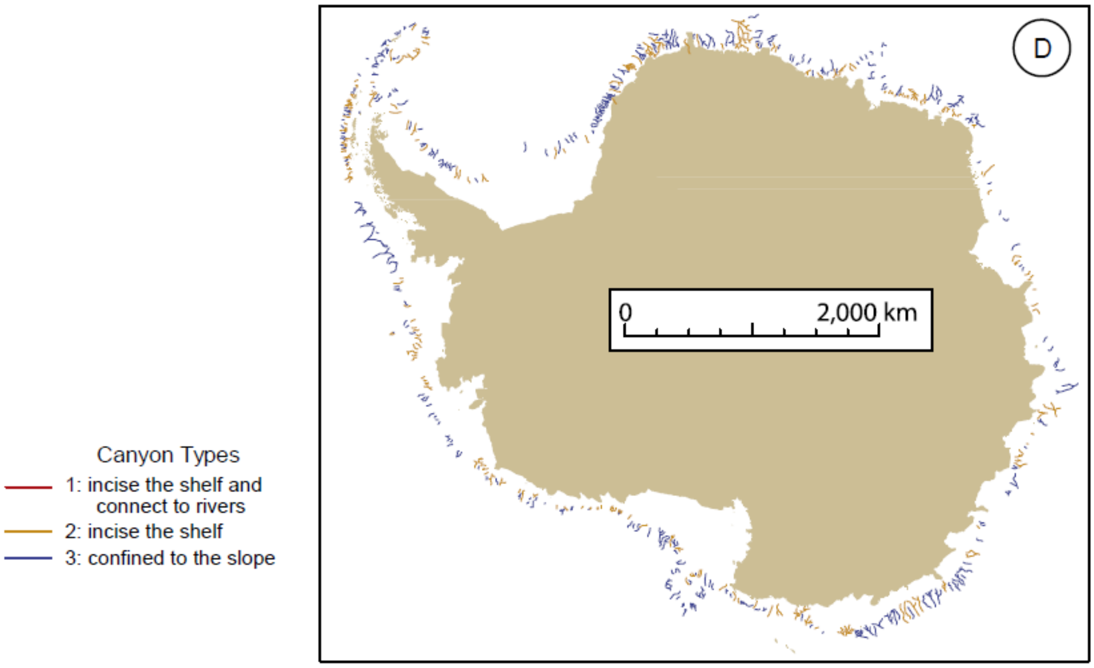


Figure 15 Canyons South Pole

3.5.1 Results

This study identified 5849 separate large submarine canyons that are resolved by the ETOPO1 data set. These are the main canyon thalwegs, and include Type 1 (river-associated, shelf incising), Type 2 (shelf incising) and Type 3 (blind, confined to the slope) canyons. In addition, they mapped 2788 dendritic limbs to these canyons making a total of 8637 separate canyon segments. The 5849 submarine canyon thalwegs have a mean length of 43.4 km, a cumulative length of 254,129 km, a mean slope of 5.1°, a mean depth range of 1992 m and a mean spacing of 33.0 km. The main canyon thalwegs together with their limbs have a cumulative length of 323,193 km.

In addition to dividing the canyons into three main Types (1, 2 and 3), the results presented below are grouped into 17 broad geographic regions that are located in either active or passive tectonic environments and in 8 variables (cumulative length, length, spacing, slope, depth range, sediment thickness, dendricity and sinuosity).

3.5.2 Occurrence and morphology of shelf-incising and blind canyon types

The 153 Type 1 (river-associated and shelf-incising) canyons mapped in this study amount to 2.62% of the total number of canyons. They have a mean length of 80.9 km (almost twice the average for all canyons), a mean dendricity of 8.3 limbs per 100,000 km2, a mean slope of 3.8°, a mean sinuosity of 1.187, a mean depth range of 2767 mand a mean spacing of 33.8 km. There are more Type 1 (shelf-incising and river-associated) canyons on active continental margins (n=119) than on passive margins (n=34). Thus, river-incised channels are more evident on narrow shelves associated with active plate margins. Type 1 canyons are most common on the western margins of South and North America where they comprise 11.7% and 8.6% of canyons, respectively. Type 1 canyons are absent from the margins of Australia and Antarctica.

The analysis revealed 1671 Type 2 (shelf-incising) canyons, equal to 28.57% of the total number of canyons, which are shorter and steeper than Type 1, have a mean length of 50.4 km, a mean dendricity of 5.0 limbs per 100,000 km2, a mean slope of 5.2°, a mean sinuosity of 1.121, a mean depth range of 2265 m and a mean spacing of 33.5 km. Type 2 canyons are most common on the margins of Antarctica and in Southeast Asia where they comprise 39.1% and 37.7% of canyons present, respectively. They are least common on the margins of New Zealand and East Africa where they account for only 20% of all canyons present in those areas.

Type 3 (blind) canyons are the most common Type mapped in this study, numbering 4025 equal to 68.82% of the total number of canyons. They are shorter than Types 1 and 2, having a mean length of 39.1 km. They have a mean dendricity of 4.7 limbs per 100,000 km2, a mean slope of 5.2°, a mean sinuosity of 1.111, a mean depth range of 1849 m and a mean spacing of 32.7 km. Australia has the highest proportion of Type 3 (blind) canyons (80.1%) followed by islands and plateaus where 76.6% of canyons are Type 3. They are least common in Southeast Asia and in the

Antarctic, where blind canyons account for only 59.8% and 60.9% of all canyons present, respectively.
To below tables is mentioned the distribution of three types around the world.

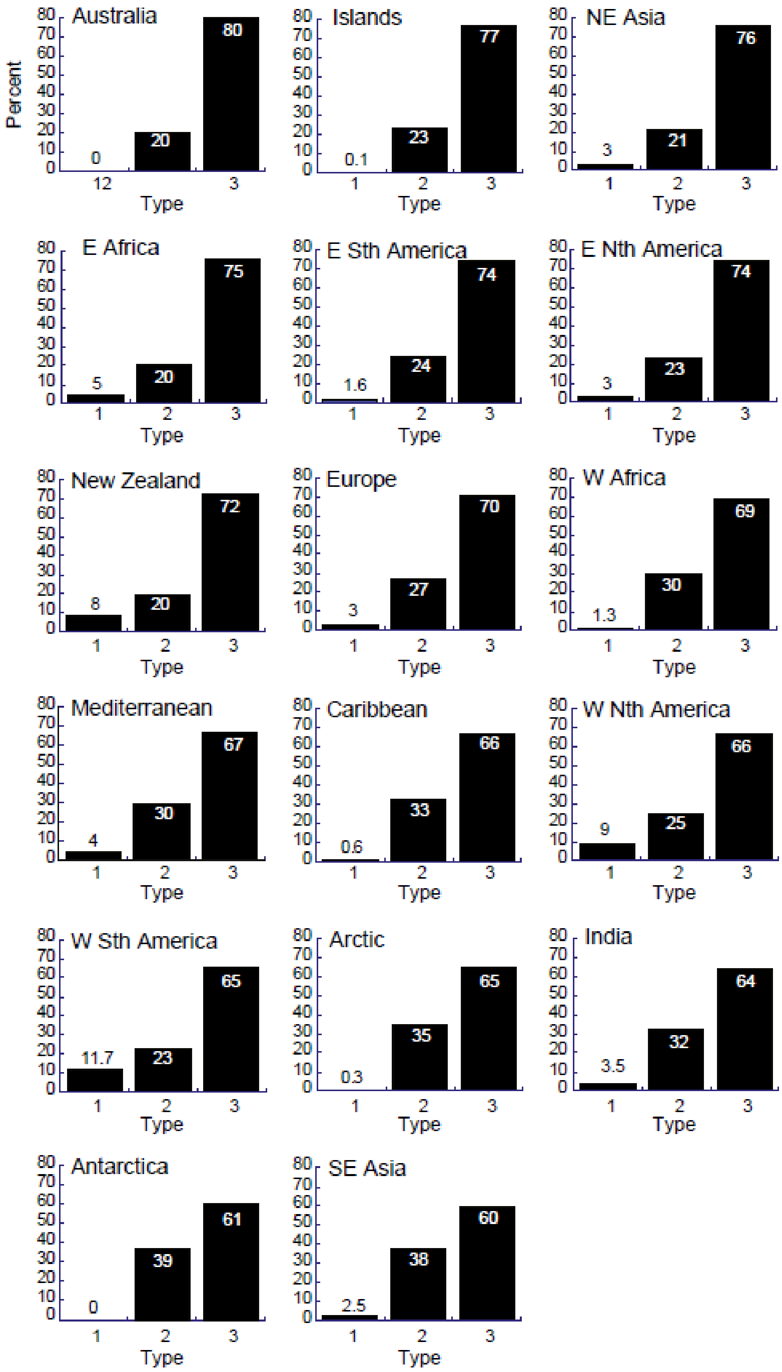


Figure 16 Bar graphs of percentage of Types 1, 2 and 3 canyons for different geographic regions.

3.5.3 Canyon length

The mean length of canyons varies regionally from 26.5 km in the Mediterranean to 65.2 km in the Arctic. The global mean length of canyons is 43.4 km. As noted above, the longest canyons are Type 1 (river associated) with a mean length of 80.9 km. Mean canyon length is negatively correlated with mean canyon slope (greater mean canyon length implies a gentler mean slope). Gentle continental slopes are wider and hence contain longer canyons than margins having steeper (more narrow) slopes. The longest canyon thalweg is the Bering Canyon on the Alaskan margin which is 411 km in length. The second longest canyon mapped in this study is an un-named canyon, 334 km in length, located in Antarctica at around 5° East longitude.

Interestingly, although the mean length of canyons is shorter on active margins than on passive margins (39.9 versus 53.7 km) the cumulative length of canyons on the two margin types is similar (~133,000 versus ~121,000 km, respectively). The greater number of canyons on active margins compensates for their shorter mean length to yield comparable cumulative lengths of canyons for both margin types.

3.5.4 Canyon slope

The mean slope of canyons varies from 2.7° for the Arctic region to 7.3° for oceanic islands and plateaus, and has a global mean of 5.1°, values that are consistent with those reported in global summaries by earlier workers. Mediterranean canyons are the second steepest, with a mean slope of 6.5°. The slope of canyons along the Antarctic and eastern North American margins are the next most gentle, both with a mean gradient of 4.4°.

Mean canyon slope is negatively correlated with mean canyon spacing (increased canyon slope implies closer canyon spacing). Since canyon slope and length are correlated, canyon length is also correlated with mean canyon spacing (greater length implies greater spacing of canyons). Canyons on active margins are steeper that those on passive margins (mean of 5.4° versus 3.8°).

3.5.5 Occurrence of dendritic canyon limbs (canyon dendricity)

Canyon dendricity is measured here as the number of canyon limbs excluding the main canyon thalwegs, occurring per unit area. Measurement of dendricity was carried out using the focal variety tool in ArcGIS, with a 185 km search radius. Values are reported as the number of occurrences of dendritic limbs per 100,000 km2. This measure thus includes both the occurrence of dendritic (branching) canyons as well as the relative concentration of the limbs per unit area.

The mean concentration of dendritic canyon limbs on active margins is 7.2 limbs per 100,000 km2, compared with 3.3 limbs per 100,000 km2 for canyons occurring on passive margins. The Mediterranean has the most dendritic canyons (12.9 limbs per 100,000 km2) whereas the Arctic has the least dendritic canyons (1.4 limbs per 100,000 km2). Type 1 canyons are more dendritic (8.3 limbs per 100,000 km2) than Types 2 or 3 (5.0 and 4.7 limbs per 100,000 km2, respectively). This study has found that dendricity is most strongly correlated with sediment thickness on passive margin. Dendricity is negatively correlated with canyon spacing (more widely spaced canyons are less dendritic), with the relationship strongest on all margin types and on active margins.

3.5.6 Depth range

Mean canyon depth range has its lowest value in the Mediterranean (1613 m) and reaches its greatest value in Australia (2363 m). Type 1 canyons are not only the longest, but they have the greatest mean depth range (2767 m) of all canyon types. However, there is no significant correlation between mean canyon length and the mean depth range of canyons. This is explained by some long canyons occurring on shallow gradient margins, whereby long canyons do not necessarily extend over a great range in water depths (e.g. Eastern North America). The mean depth ranges of canyons on active versus passive margins are nearly identical (2003 versus 1984 m).

3.5.7 Canyon sinuosity

Canyon sinuosity is the dimensionless ratio of the length of the canyon thalweg (measured as the cumulative distance between adjacent points digitised along the thalweg) divided by the linear distance between canyon start and end points. A straight line has a sinuosity of 1 (the minimum possible sinuosity), and all curved and winding thalwegs have a sinuosity N1. It is thus clearly important to know the number of digitised points measured along the canyon thalweg, since at least three points are needed to measure any amount of canyon sinuosity. In this study the 5849 separate canyons have been digitised by 90,779 points, which is an average of 10.5 points per canyon segment, and an average of one point every 3.56 km.

This study has found that the mean sinuosity for all canyons is equal to 1.111. Sinuosity is not significantly different (at 95% confidence intervals) between active and passive margins (sinuosities of 1.124 and 1.102, respectively). Types 1, 2 and 3 canyons have sinuosities that are not statistically different from one another (at 95% confidence intervals). The Arctic and Antarctic canyons are the least sinuous (1.079 and 1.098, respectively) and their mean values are significantly different (at 95% confidence intervals) from canyons on the western margins of North and South America (1.226 and 1.215, respectively), which have the greatest sinuosity of the major geographic regions examined in this study.

The correlation between sinuosity and other parameters measured for canyons in this study is greatest for depth range for all margin types, for cumulative length for passive margins, and slope for active margins. Sinuosity also has a moderate correlation with the length of canyons on active margins.

		Active Margins	Passive Margins
	Canyon Occurrence (number)	2,586	2,244
	Type 1 Occurrence (number)	118	34
Mean values	Slope (Degrees)	5.4 ± 3.5	3.8 ± 2.7
Mean values	Spacing (km)	26.5± 21.5	39.2 ± 38.2
Mean values	Length (km)	39.9± 34.0	53.7 ± 40.8
Mean values	Dendricity (per 100,000 km^2)	7.2 ± 6.6	3.3 ± 4.1
Mean values	Sediment thickness (m)	944 ± 1120	2,624 ± 2549
Mean values	Depth Range (m)	2,003 ± 878	1,984 ± 842
Mean values	Sinuosity	1.133 ± 0.183	1.102 ± 0.127
	Cumulative Length (km)	114,913	121,000

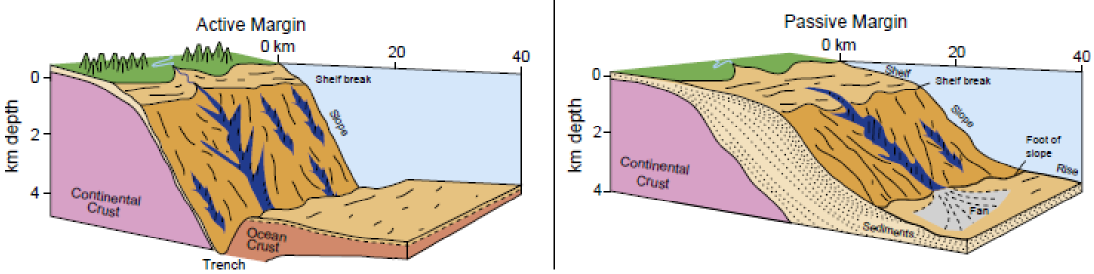


Figure 17 Generalised, schematic 3D diagram contrasting the geomorphic attributes characteristic of submarine canyons occurring on passive and active continental margin types.

3.6. Factors Controlling / Affecting Canyon formation

3.6.1 Long term controlling factors

Submarine canyons are erosive features occurring across continental margins that result from the interplay of three major controlling factors: (1) Geodynamic setting and structural controls, (2) Depositional/erosive processes, (3) Sea level changes.

In the long term, canyon formation is strongly controlled by the allogenic processes connected with the geodynamic setting and the structural framework that create continental margins. In the Mediterranean Sea and in the Sea of Marmara, many continental margins are the result of recent extensional processes that have led to steep slope gradient and, often, narrow shelves. During the rifting episodes, various sets of faults were created along the Mediterranean margins that later became preferred sites for canyon formation. Rifting and foundering processes also result in the flooding of sub-aerial valleys that are progressively invaded by the sea and can consequently become submarine canyons. Rift areas are also affected by strong uplift of hinterland areas. Such a geodynamic process is capable of creating high relief coastal ranges often carved by rivers with mountainous regime with high energy flooding events that erode the continental slope, particularly in areas with narrow shelves. In the latter cases (e.g., French Riviera, Calabria, Algeria, Sicily), the terrigenous river inputs are directly transported to canyons and energetic high volume sediment gravity flows can contribute to their deepening.

In the Mediterranean Sea, canyons also develop along compressive continental margins where high gradient continental slopes are maintained by thrust tectonic and folding. Here, structures have in general a trend parallel to the margin, and canyons with alternating slope-parallel and slope-transverse tracts often occur in the crossing of accretionary wedges.

Tectonics, through the activation and deactivation of single faults, also controls canyon evolution on smaller time scales. On active or re-activated margin segments (e.g. Calabria, Algeria, Southern France, Sea of Marmara) fault evolution can cause renewed slope steepening and canyon excavation and enlargement, canyon abandonment and changes of canyon courses.

The origin of submarine canyons is also intrinsically tied to erosional processes occurring on continental slopes. On open slope regions, different kinds of unconfined gravity flows may use irregularities of the seafloor of any origin (i.e. slide scars, seepage depressions, faults, etc.) as preferential paths, resulting in the self-organisation of gravity driven flows and finally leading to canyon formation. Mass wasting along continental margin plays perhaps the most important role in creating areas where flows are gradually focused and finally confined during the initial phases of canyon excavation. Mass wasting processes are usually enhanced by high sedimentation rates; thus sediment input at margin scale and areas with high sedimentary fluxes can control the timing and location of canyon formation. In addition, mass wasting processes are often characterized by a retrogressive pattern of erosion that can eventually lead to shelf-break indentation favouring the connection between slope erosional areas and sediment input from the coastal areas (Micallef *et al.* 2014). In this way canyons are established as erosional fairways where transport of sediment from the shallow coastal areas to the deep sea is accomplished.

Submarine canyons, as long-life geomorphic elements, are affected by sedimentary processes that are highly variable in time. Following the initial phase of canyon excavation, fluctuations between erosional and depositional regimes will usually take place until a canyon is completely filled and ceases its activity. The evolution of erosional and depositional processes within canyons results from the complex interplay between various controlling factors that act at different temporal and spatial scales. These key parameters, that can be allo- and auto-genic, are summarised in Fig. 18 in relation to their respective duration.

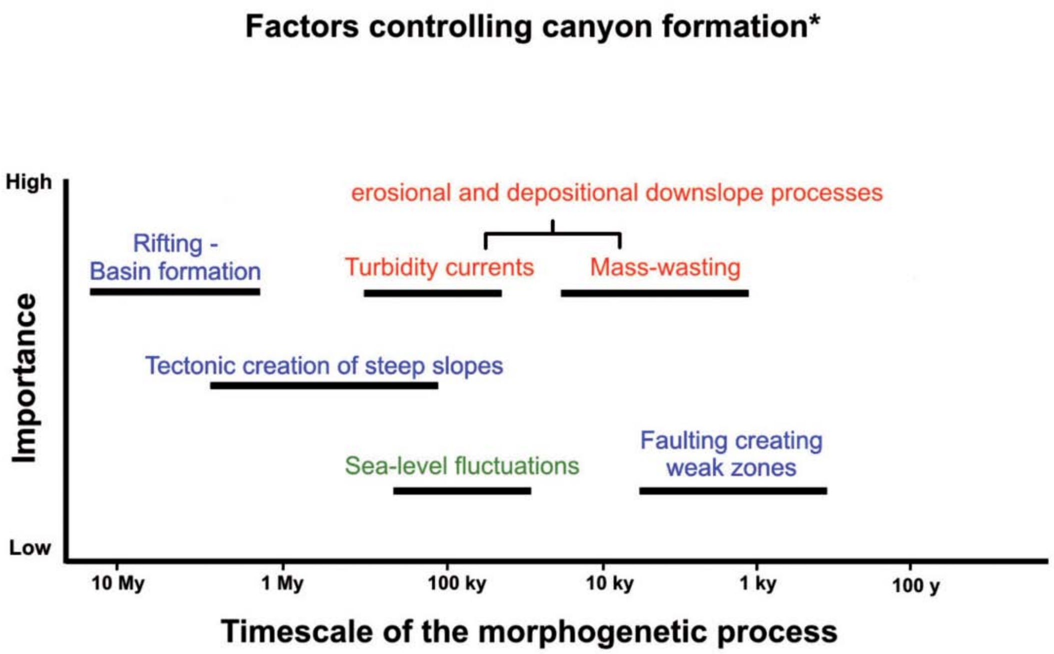


Figure 18 Factors controlling canyon formation over geological time.

Sea level change is of course another important allogenic factor controlling canyon nucleation and evolution. Around the Mediterranean basin, the Messinian event that resulted in a "geologically sudden" sea level drop played a specific and major role in canyon evolution. During the Messinian in fact most of the present day continental slopes were reshaped by sub-aerial erosion, with the upper parts of many present-day canyons acting as rivers.

Sea level variations of smaller amplitude are also particularly relevant to the canyons of the Mediterranean margins. The alternation of glacial and interglacial periods that occurred repeatedly during the last 2.5 Ma is indeed responsible for many of the features of present-day canyons. They cause eustatically-controlled coastal advancement and retreat that are particularly important in driving the energy and the volume of the flows that enter canyon heads. Canyons with heads located at the shelf break, far from the coastline, are at present mainly sediment starved and undergoing a passive infilling phase. However, their morphology can still provide a record of the processes that were active during the past lowstands of sea level, when they were connected to rivers. As the Mediterranean shelf is often quite narrow, many canyon heads remain connected to the coastal area during the present highstand of sea level. In this context, hyperpycnal flows, storm reworking and long-shore current transport can feed sediment to the canyon heads that are then shaped by active processes of erosion, sediment transport and deposition along the canyon axis. Once the submarine canyon is formed, the same factors will keep on controlling its morphological evolution and the canyon will evolve through autogenic process (trending to equilibrium).

Figure 18 summarizes the principal factors controlling submarine canyons formation and evolution over the long-term:

1) Geodynamic setting and structural controls:

a. Rifting,

b. Basin formation,

c. Creation of coastal range,

d. Presence/absence of continental shelf and coastal plane,

e. Tectonics (creating steep continental margin slopes),

f. Faulting (creating weak zones).

2) Depositional / erosional processes:

a. Self-organization of gravity driven flows: before canyon formation any kind of unconfined gravity flow will use irregularities of the seafloor of any origin (i.e. slides, seepages, faults) as preferential paths, resulting in self-organisation that will end with canyon formation.

b. Sediment input on margin scale: discharging downslope sediments, sedimentary flux, turbidity currents, confined morphologies.

c. Mass wasting, retrogressive erosion, high sedimentation rate (favour remobilization and determine how prone is a slope to fail).

3) Sea level changes

a. Importance of Quaternary sea level fluctuations in submarine canyons formation and evolution.

b. Messinian event, a specificity of the Mediterranean basin which contributed to reshape most of its continental slopes.

3.6.2 Natural and human-induced factors affecting canyon dynamics in historical time

Submarine canyons can be affected by natural processes that strongly differ in nature, intensity, frequency and spatial/temporal scale. The short-term processes interesting submarine canyons are meant here as those occurring since the initiation of the present sealevel highstand stage, around 6 kyr BP. They match the actual geologic and oceanographic scenarios of continental margins.

They involve oceanographic and sedimentary dynamical processes affecting the physical and chemical setting along canyons (seafloor and/or water column): examples are storms, dense water cascading, internal waves, river floods, turbidity currents, debris flow, canyon flank avalanches and collapses. Human activities, especially deep-sea trawling fisheries developed at industrial scale in the last 50 years may be included in that category.

The natural and human-induced processes maintaining canyon dynamics do strongly differ in space and time. Large oceanographic events, such as dense shelf water cascading, and extensive turbidity currents, can affect the sedimentary environment and the habitat distribution at the scale of an entire continental margin, developing for thousands of km from the canyon head to the deepest sectors of the depositional channels. On the other hand, small-scale mass movements or internal waves and tides can be localized in specific canyon areas, such as canyon heads or flanks. Defining the minimum scale of processes for which a canyon can be considered a dynamic environment is still an unresolved issue.

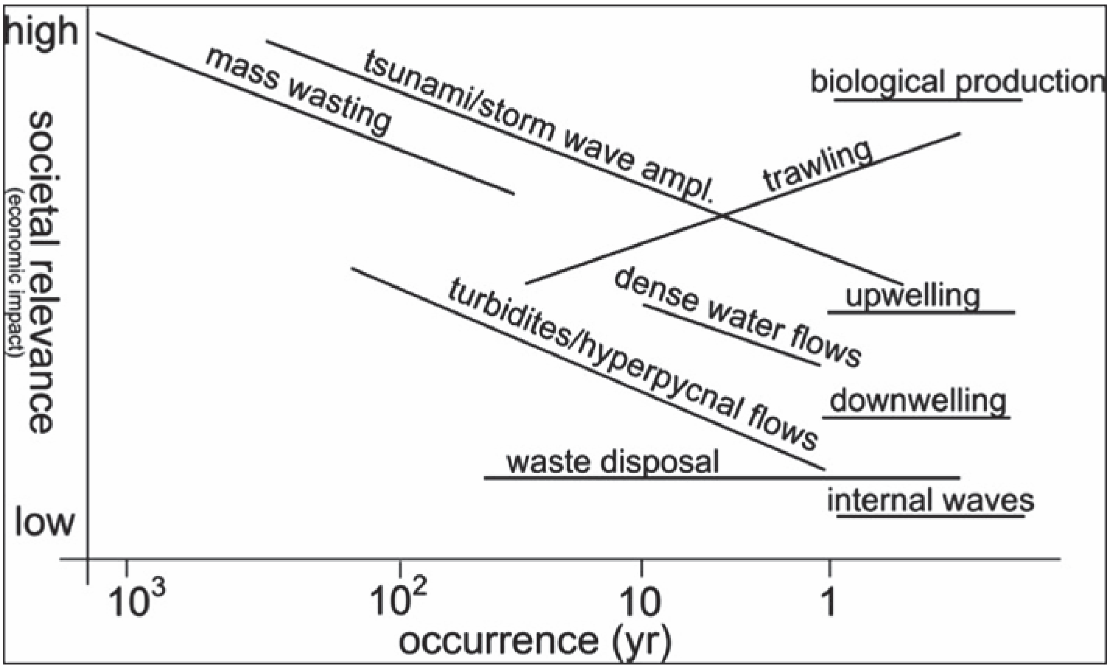


Figure 19 Factors affecting canyon dynamics over the short term.

Important gaps in knowledge have been filled in recent years thanks to comprehensive research, but a solid understanding of canyon dynamics is still lacking. We note, for example, a critical absence of integrated datasets, which would include sedimentary, ecological and oceanographic observations over long time spans. This is due in part to the evident mismatch between the spatial and temporal scales of observations of various scientific groups working on canyon-related topics: they often observe the same natural phenomena under different perspectives.

3.7 Water circulation submarine canyons

3.7.1 Matter and Energy Transfer Across Submarine Canyons and Open Slopes

It has long been believed within the scientific community that submarine canyons are preferential conduits for the transfer of matter and energy from coastal areas and continental shelves to the deep ocean. However, it is only recently, over the last two decades, that both long-term and high-frequency in situ measurements have provided a wealth of data illustrating the efficient and seasonally modulated export of sedimentary particles along Mediterranean margins, preferentially through submarine canyons.

In simple terms, gravitational effects enhance trapping and downslope transport of particles within canyons compared to adjacent open slopes. To some extent, this is the same reason that water flows down along river valley axes (i.e., the topographic gradient determines flow direction and transport). However, in the ocean, the density contrast between particle-laden waters and surrounding clearer waters is much smaller than that between riverine freshwater and the surrounding air, for instance. Other processes, such as geostrophic circulation, can therefore interfere with particle transport and accumulation in the ocean. It should also be noted that sediment-laden waters can be either denser or lighter than surrounding waters. Consequently, these particle-laden layers, often called “nepheloid layers,” occupy a position in the water column according to their relative density. When they immediately overlie the seafloor, they are called “benthic nepheloid layers.” All types of nepheloid layers—superficial, intermediate, and benthic—can spread over open slopes and submarine canyons, though the benthic nepheloid layers and sometimes the intermediate types tend to be more developed in submarine canyons.

Particles exported beyond the continental shelf to the deeper environment originate from various sources. Allochthonous sources include aeolian dust (e.g., from North African deserts), sediments and pollutants transported by rivers, particles carried in suspension from afar by mesoscale ocean currents, and sewer discharge and ship tank cleaning. Autochthonous sources include biological production, erosion and resuspension of seafloor materials by waves and currents, landslides, and anthropogenic activities such as anchoring, dredging and, especially, trawling. In historical times, human activities both on land and at sea have had strong indirect and direct impacts on particle concentrations in ocean waters, either by increasing the particle load released to the sea (e.g., because of agricultural development or deforestation that has increased erosion of river basins, thus adding to particle discharge at river mouths) or by decreasing it (e.g., because of river damming). Direct disturbance of the seafloor by trawlers and other activities certainly adds significant volumes of particles that remain in suspension for variable periods, depending on the intensity of the activity itself, the grain size and density of the particles, and the energy level of each specific area.

The study of matter and energy transfer across continental margins, which includes particle transfer, is not only of scientific relevance but also of the utmost interest for environmental, economic, and societal reasons. Only by understanding particle transfer in the ocean will we be able to understand how deep ecosystems are fueled, and to determine their capacity to capture and store carbon. Improving our understanding of natural carbon storage and quantifying it is one of the greatest challenges our society faces in view of ongoing global warming. Investigating particle fluxes is also important to better understand the transfer and fate of pollutant loads to the deep ocean, which affect living resources, including commercial species. It is also of interest to know how, where, and under what conditions hydrocarbon reservoirs formed in the past, which may allow better search strategies to be developed—a key issue in view of the increasing worldwide pressure on energy resources.

At next chapter the relation between canyons and ecosystem will be investigated more.

3.7.2 Circulation mechanism

Submarine canyons can affect general and local scale circulation patterns by deflecting the in-coming and out-coming flows. Several key factors play a role by enhancing or reducing the canyon effect, i.e. the canyon's relative position (distance) from the coast, its size and morphology, general circulation and local currents, the in-coming flow direction, the presence, intensity and amount of river outputs and wind stress strength, water mass stratification, etc. The result is a great variety of situations and effects which can occur for each single canyon (or each canyon system) set along the continental margin of the Mediterranean, and which are, in some cases, very different from what could be expected through oceanographic process modelling.

The tendency of geostrophic circulation to follow bathymetric contours limits the cross shelf-break exchanges. Canyons cutting the bottom topography can reduce the rotational effects of the current (geostrofic effect such as Coriolis force) and significantly force the flow to cross isobaths, leading to enhanced mixing through upwelling and downwelling.

Specially at Mediterranean, the circulation is mainly characterized by a large cyclonic gyre of in-coming Atlantic waters, which can generate anticyclonic eddies on the coastward right side of the flow, strongly affecting current patterns within the continental shelf. On the left side of the gyre flow cyclonic eddies are generated, which can affect circulation in the pelagic domain from the continental margin to far offshore. Bottom morphology (seamounts, submarine canyons, gullies, trenches, valleys, steep slopes, etc.) as well as wind forcing and increasing density processes can alter and deeply modify the above patterns, thus a high time-volume variability is the main feature of Mediterranean circulation.

Nevertheless, in spite of this high variability, we can try to recognize some general features (processes) generated by circulation canyon interaction:

— Near-bottom currents are constrained to the topography and closed circulations are observed in the canyons, while near surface flow is unaffected by the underlying topography under real stratifications. Flow across the canyon leads to localized upwelling and downwelling.

— When the flow has the coast on its right (a right-bounded flow), the current-canyon interaction causes asymmetry in the vertical velocity field; downwelling is forced over the upstream wall, whereas upwelling is forced over the downstream wall (Fig. 20). In the northern hemisphere, flow propagating along the shelf/ slope direction with the shoreline on the right is called “positive along-slope flow” (Fig. 21). Positive flows are associated with net downwelling (downward flow and flow toward the ocean).

— When the in-coming current has the coast on its left (a leftbounded current), the current-canyon interaction causes local upwelling over the entire canyon. In the northern hemisphere, flow that travels along the slope with the shoreline on its left is referred to as “negative along-slope flow”. Generally, negative flows are associated with net upwelling (upward flow and flow toward the coast).

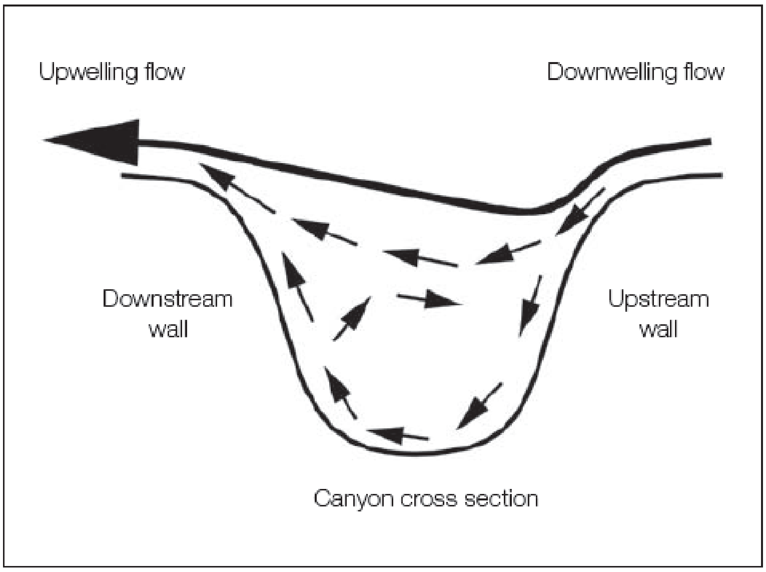


Figure 20 Schematic representation of a right-bounded flow (when the flow has the coast on the right

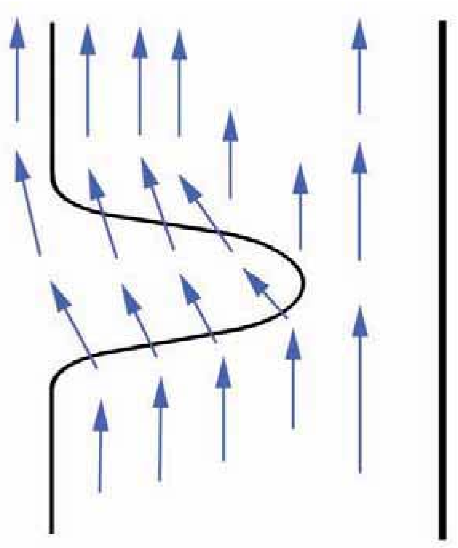


Figure 21 Positive flow in the Northern Hemisphere. Plan view sketch showing net flux through a canyon onto the shelf, accommodated by an increasing along-shelf flux. The black line is the shelf-break isobath, straight hatching on the right indicates the coast, and the blue arrows represent the flow.

— Canyons in the Mediterranean are generally under the influence of positive flows
— Narrow canyons have a strong effect on circulation and are characterized by a general cyclonic circulation within the canyon rims (Fig. 22).
— Wide canyons only modify the circulation along the topography.

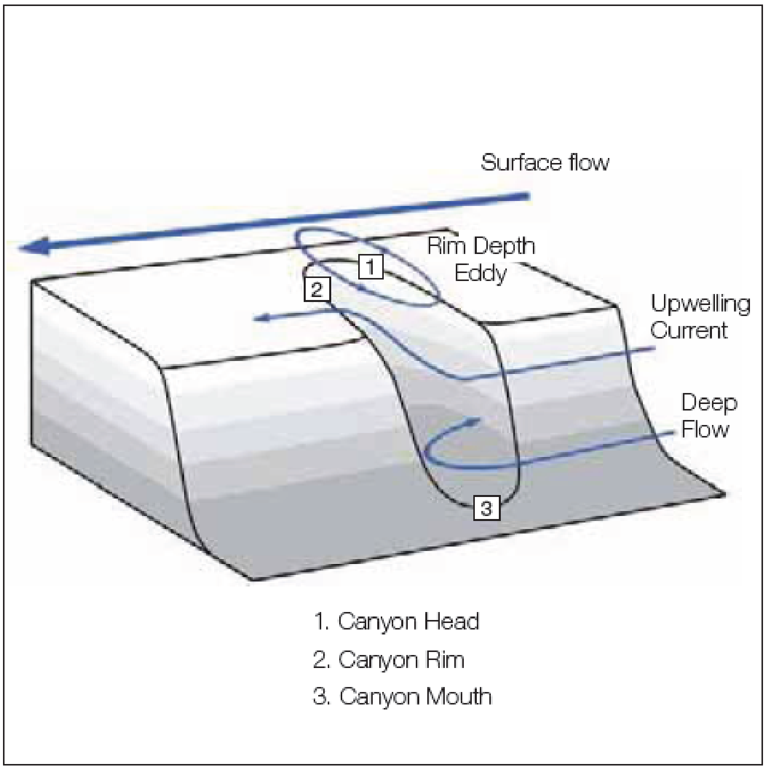


Figure 22 Wind-driven shelf-break or slope currents lead to upwelling or downwelling flows within the canyon, with the strongest effects at the canyon rim especially at shelf-break depth

One other study separates canyon conduit flow into two types:
— Wind-driven shelf-break or slope currents lead to upwelling or downwelling flows within the canyon, with the strongest effects at the canyon rim especially at shelf-break depth (Fig. 23).
— Deep water formation on the shelf similarly leads to strong cross-slope pressure gradients. However, these flows cascade down the canyon, are focused deep, near the canyon axis, and are, in many ways, independent of the wind-driven flows above.

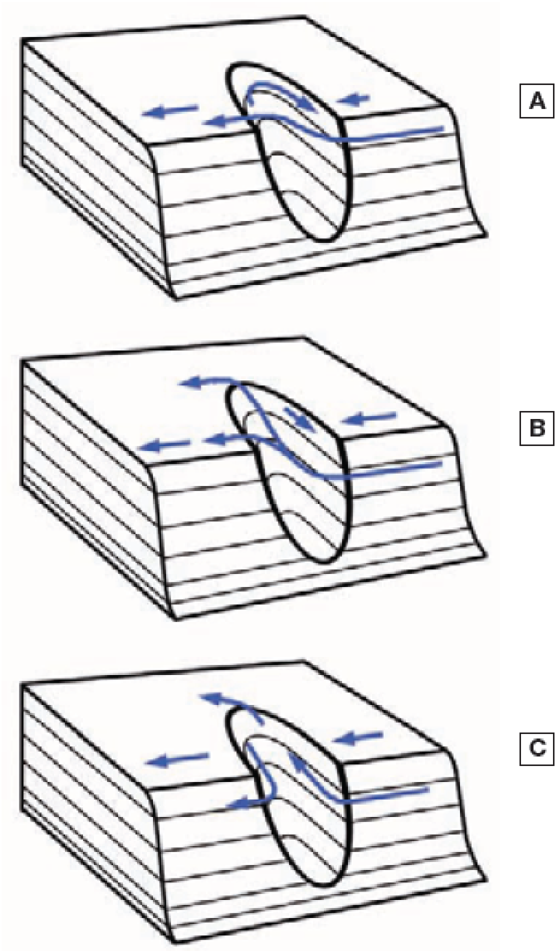


Figure 23 Schematic representation of three upwelling mechanisms within submarine canyons:
A) isobath convergence,
B) advection and
C) time dependence of the flow

Net fluxes to or from the ocean can be accommodated by changes in the along-shelf current. Waterhouse *et al.* (2009) described possible mechanisms driving upwelling due to different flow dynamics between the long and short canyons: isobath convergence, when long canyons,which closely approach the coast, have strongly converging isobaths (Fig. 23 A); advection, short canyon flow show this upwelling regime in the case of low Coriolis force effect (Fig. 23 B), and time dependence upwelling occurs with the lowest incident flow velocity in the short canyon (Fig. 23 C).

In the same study is distinguished three phases during the upwelling or downwelling scenario due to oscillatory coastal wind effects:
— An initial time-dependent response, as the shelf-break flow increases. It is generally strong and occurs quickly. If the along-shore current continues to increase (i.e. because of steady winds), density advection within the canyon reduces time-dependent upwelling after about 5 days.

— An advection-dominated response during the time when the shelf-break flow is reasonably steady. It is strongly dependent on the canyon topography and flow strength. For weaker flows it can be greatly enhanced if strongly convergent isobaths occur over the canyon.
— A relaxation phase, when the shelf break flow decreases. A strong, generally cyclonic flow occurs within the canyon.

During the second phase, upwelling is generally stronger than downwelling. This last is driven by positive flow and does not impede the along-isobath flow. On the other hand, upwelling flow opposes the shelf current leading to a strong cross-isobath flow over the canyon walls (Fig. 24). Thus, in the positive flow phase, the current diverges from the upstream wall and flows out of the canyon along the downstream wall. In the negative phase, the flow follows the upstream wall into the canyon and upwells along the downstream wall.

This generalized pattern can be modified by various factors: in Blanes canyon, for example, the presence of cold and fresh waters coming from the Gulf of Lion continental shelf causes the flow reversal above and just below the thermocline. This fact reinforces the observation that no individual canyon is identical to another.

Inputs from landmasses strongly influence Mediterranean ecosystems, as a huge amount of organic and inorganic matter from continental and shelf sources can reach the deepest basins by means of fast, dense, organic-matter-rich and sediment-laden near-bottom currents occurring from winter to early spring, through continental margins and submarine canyons.

Seasonal cooling and evaporation generate denser seawater at the uppermost layers; favoured by a decrease of river discharge reducing their buoyancy, the surface water masses sink. The northern shelves of the Mediterranean (i.e. the Gulf of Lion, Adriatic Sea and Aegean Sea, more exposed to cold and intense northerly winds) are the main source areas of these density-driven currents (see also Company *et al.*, this volume), which are known as Dense Shelf Water Cascading (DSWC). Cascading may last for several weeks, and waters sink until their density equilibrium is reached. Intense DSWC events, which can carry shelf waters to the deepest parts of the Mediterranean basin, seems to occur at subdecadal frequency.

Submarine canyon size controls the volume of cascading waters, on the other hand cascading acts on canyon morphology, enhancing erosion or sedimentation. A canyon degrades and sooner or later becomes buried when it loses its sediment transport capacity; a canyon enlarges or increases laterally and longitudinally if it maintains its sediment transport efficiency.

In one study, is developed the concept of “flushing submarine canyons” in order to describe the role of canyons as main conduits for cascading. When the water volume is too large, the canyon, depending on its size, cannot accommodate it, therefore waters overflow the canyon rims as “laminar flow” sweeping the continental slope before spreading over the deep basins.

As cascades may simultaneously occur with spring phytoplankton blooms, their consequences on the deep ecosystem of the Mediterranean Sea and their role as a natural mechanism for carbon sequestration in shallow ocean layers will need better knowledge in the coming years.

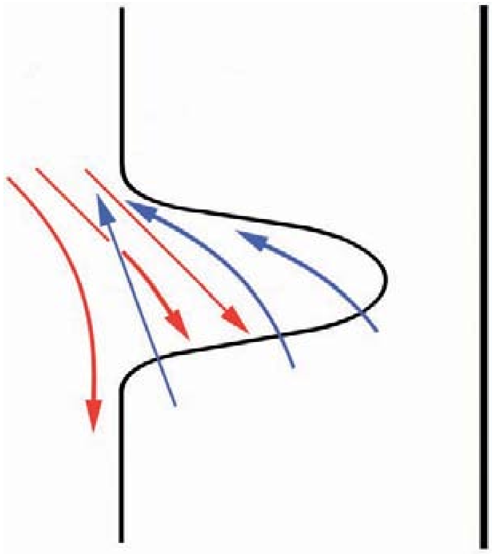


Figure 24 Plan view sketch showing differences between the positive (blue) and negative (red) phases of oscillating flow for the Northern Hemisphere. The black line is the shelf-break isobath, the straight line on the right indicates the coast, and the blue and red arrows represent positive and negative phase flow respectively.

CHAPTER 4

SEDIMENT TRANSPORTATION MECHANISMS

As we have discussed, submarine canyons are morphological features that are found on many continental margins, acting as preferential conduits for transport of sediment from continental shelves towards deep-sea environments. During Plio-Pleistocene lowstands of sea level, sediment–gravity mechanisms (i.e. turbidity currents, debris flows) dominated transport through submarine canyons, funneling large volumes of terrigenous sediment to deeper parts of the continental margins. Although Holocene sea-level rise has reduced drastically the supply of sediments to submarine canyons, it is widely recognized that canyons at present continue to be preferential conduits for the transfer of sediments from the shelf to the deep ocean.

4.1 Main mechanism

During the last decades, several studies have provided information about contemporary sediment-transport processes acting within submarine canyons by means of analysis of combined currents and suspended-sediment concentration data.

The most important are presented below.

4.1.1 Storm-induced resuspension of shelf sediments,

From the coast to the deep ocean, one of the main processes of sediment transfer is turbidity current flowing into submarine canyons. Turbidity flows are mostly responsible for submarine erosion of the upper slope and canyon incision. Submarine canyons are mainly located in the continuity of the major drainage networks. Continuity of fluvial sediment fluxes in the canyons is often indirect because of the presence of a shelf and of coastal hydrodynamic settings (waves, tides, currents) that redistribute sediments along the coast.

The origin and the triggering of turbidity currents are still discussed aspects. Scientific issues include the continuity at sea of hyper-concentrated stream flows generating hyperpycnal flows into canyons, mass wasting and re-suspension of sediment deposits under the influence of oceanographic factors (waves, currents).

The study of turbidite processes and their triggering can be addressed in several ways: with the study of modern turbidite systems on the seafloor (Piper and Normark, 2009), with numerical or physical modelling of flow processes (Eke et al., 2011),with monitoring of active currents with current metres and moorings (Johnson et al., 2001; Puig et al., 2003; Liu et al., 2006; Palanques et al., 2006; Puig et al., 2008; Paull et al., 2010), or the simple observations of communication cable breaks (Heezen and Ewing, 1952; Hsu et al., 2008; Cattaneo et al., 2012). Monitoring and in-situ measurements of turbidity currents are particularly difficult because the gravity events occur occasionally with long recurrence time and their occurrence cannot be anticipated. In addition, the turbidity flows responsible of largest morphological changes are difficult to measure because they damage instruments (Khripounoff et al., 2003; Paull et al., 2003). Only weaker and small scale turbidity currents can be recorded from in-situ experiments (Xu et al., 2004; Mulder et al., 2012; Xu et al., 2013).

In recent years, high-resolution bathymetric data acquired with latest-generation multibeam and sonar technologies also provides advances in outlining submarine morphological features, and in understanding the sedimentary processes in canyons, and especially at the canyon heads.

4.2.2 Hyperpycnal currents,

The across and off-shelf transport of sediment also changes as a function of short-term high-energy events such as river floods. River floods increase the transfer of terrigenous material to the coastal area that can be subsequently remobilized during storms. When a storm coincides with a period of high river discharge, suspended sediment concentrations are considerably enhanced, leading to an increased export of shelf sediment to submarine canyon and the continental slope at large.

One example is the Blanes submarine canyon (BC) deeply incises the Catalan continental shelf in the NW Mediterranean Sea. As a consequence of the closeness (only 4 km) of its head to the coastline and the mouth of the Tordera River, the canyon has a direct influence on the shelf dispersal system as it collects large amounts of sediment, mainly during high-energy events.

The Tordera River and several torrents, such as the Tossa de Mar and Lloret de Mar ones, fed the continental shelf of the BC area (Fig. 25A). Their sediment input depends directly of the rainfall regime, which is characterized by long dry periods interrupted by short, strong events that can result in floods within a few hours, especially in the case of eastern storms carrying wet air against the coastal relieves. The Tordera River catchment area covers 879 km2 and has a maximum altitude of 1684 m and a mean slope of 3.8^{o}. The Tordera River headwaters are located in the Montseny- Guilleries Massif and the Pre-Littoral Chain. The drainage system is incised to a large extent in the granites of the Catalan Coastal Ranges (Fig. 25A). The Tordera River releases to its mouth high amounts of coarse immature sands carried as bedload and fine sediment in suspension. Sand sizes represent approximately 83% of the total sediment discharge of the river. The immature character of these sediments is due to the nature of source rocks, to the relatively short distances travelled and to the dominant fast flood torrential regime of the river.

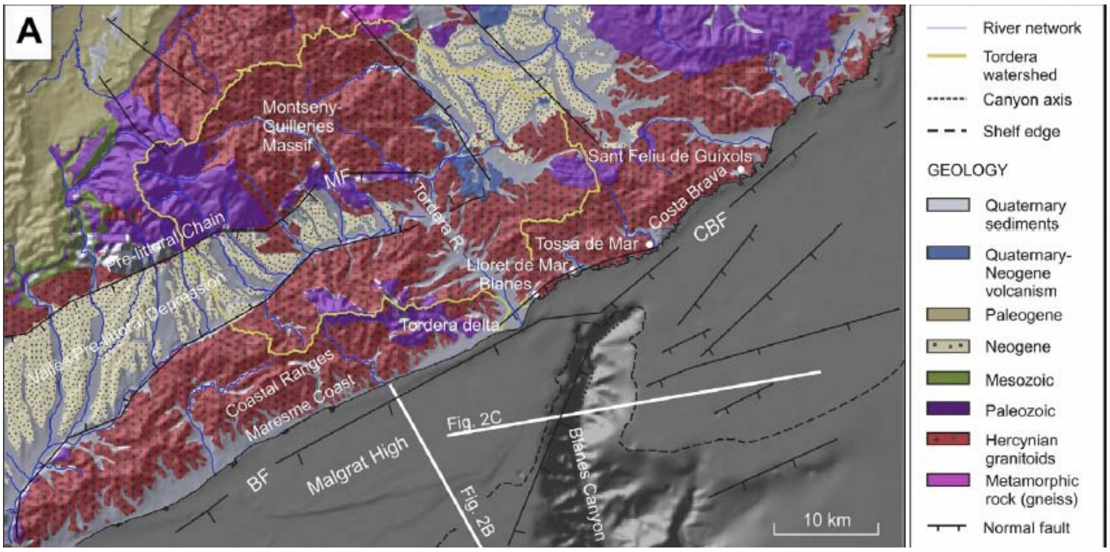


Figure 25 Geological map of the Blanes coastal area. The offshore structural elements have been synthesized from Serra (1976), Bartrina et al. (1992), Mauffret et al. (1995) and Maillard and Mauffret (1999) and the onshore structure is adapted from IGC-ICC (2010). BF: Barcelona Fault. CBF: Costa Brava Fault. MF: Montseny Fault.

Sediment deposition by the Tordera River and smaller streams, such as Lloret de Mar and Tossa de Mar torrents, has led to the formation of small submarine prodeltas off the river mouths. They display very high backscatter, which is indicative of the coarse nature of the sediments supplied by these water courses (Fig. 25A). The bulging to elongate shape of these features results from the predominant southwards littoral drift that distributes the sediment delivered by these streams southwards along the inner shelf. This alongshore transport is also evidenced by the formation of a large submerged sand spit that extends southwards off the Tordera River mouth, as described by Serra et al. (2003, 2007).

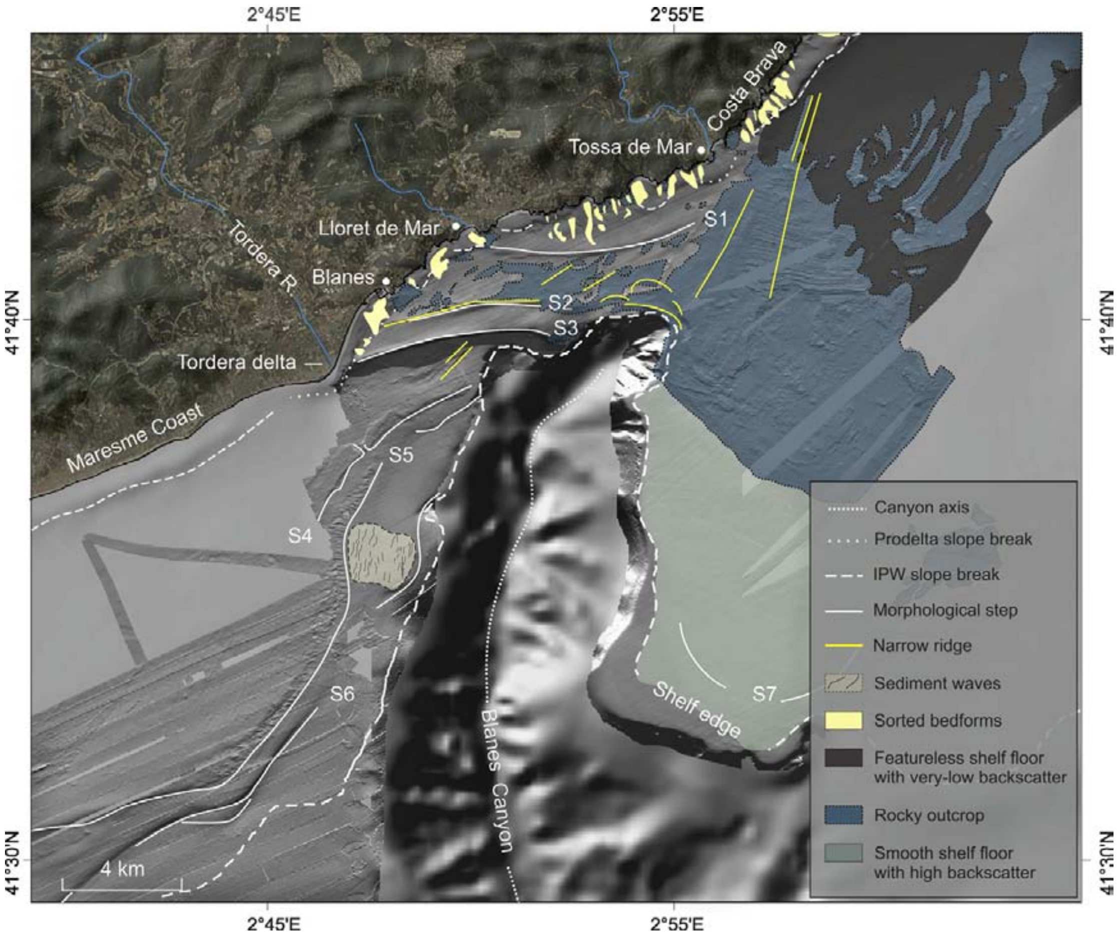


Figure 26 General shaded relief map of the study area showing the main geomorphic elements commented in the text.

4.2.3 Submarine slope failures,

Submarine slope failures are known to generate and maintain upslope migrating bedforms such as crescent-shaped bedforms (CSBs) in other canyon systems, especially where sediment supply to the head of the canyons is high. These slope failures occurred during major earthquakes or due to high sediment supply.

Additional information have been included in chapter 3.2 and 3.3

4.2.4 Dense shelf water cascades

Dense shelf water cascading (DSWC) is a meteorologically-driven oceanographic phenomenon occurring not only on high latitude continental margins, but also on mid latitude and tropical margins (Ivanov et al., 2004). DSWC is a specific type of buoyancy driven current, in which dense water formed by cooling, evaporation or freezing in the surface layer over the continental shelf descends down the continental slope to a greater depth. The same phenomenon is also referred to as near-boundary convection or also as shelf-slope convection, to be differentiated from the open-sea convection (Killworth, 1983).

DSWC sites have been identified in many continental margins around the world, mostly on the basis of cross-margin hydrographic sections (see Ivanov et al., 2004), since time series observations from this oceanographic phenomenon are scarce. The Gulf of Lions continental margin, in the north western Mediterranean Sea, is one of the known regions where this phenomenon occurs on an annual basis (Durrieu de Madron et al., 2005) and from where DSWC events have been continuously monitored during the last decades (e.g., Heussner et al., 2006; Palanques et al., 2006; Canals et al., 2006; Puig et al., 2008; Ribó et al., 2011; Palanques et al., 2012). Dense shelf waters are formed along the Gulf of Lions coast by cold and dry northerly winds (Tramontane and Mistral), and are transported along the shelf as a bottom layer towards the southwest, until they cascade preferentially into the Cap de Creus Canyon. These DSWC can be triggered or enhanced during storms events and last for several days or weeks, and the associated strong currents (up to 100 cm s^{-1}) can induce erosion and resuspension of surface sediments on the outer shelf/upper slope (Canals et al., 2006; Ogston et al., 2008; Puig et al., 2008). Detailed observations for DSWC flows also exist in the Adriatic Sea. In this region, dense waters are formed in the northern Adriatic shelf, also by cold and dry northerly winds (Bora), and are advected along the shelf towards the south until cascading in the southern Adriatic Pit, partially via the Bari Canyon (Trincardi et al., 2007; Turchetto et al., 2007; Verdicchio et al., 2007).

4.2.5 Internal tides/waves

Internal tides/waves can generate strong up- and down-canyon currents in many submarine canyons around the world to depths down to ~800 m. These up- and down-canyon movements are often related to the semi-diurnal (M2) component of the tide, which lead many authors to conclude that they are frequent processes for sediment suspension within the head of submarine canyons. Currents generated by internal waves can exceed 0.5ms−1 on sloping topography, which can be sufficient to mobilize sand-size particles. Xu et al. (2008) suggested that relatively slow moving currents related to internal tides could be responsible for their migration, but they assumed that the bedforms migrated downslope. Because coarse material, cobbles and mud clasts were found in the CSBs of various canyons, it was improbable that slow-moving tidal currents would be responsible for their migration.

An integrated study conducted by Gardner (1989a, b) in Baltimore Canyon using moored current meters and transmissometers clearly revealed that sediment from the canyon floor between 200 and 800 m was resuspended regularly when energy of internal tides was focused along the canyon axis. Analysis of time series was used to describe a mechanism consisting of a bore of cold water with a turbulent head moving up-canyon that resuspended sediments, resulting in a sharp peak of SSC at the beginning of the event, followed by a smaller and more continuous increase in SSC that corresponded to the downcanyon advection of the resuspended particles. The same resuspension mechanism was inferred in Hudson Canyon (Hotchkiss and Wunsch, 1982) and observed to occur in the Guadiaro Canyon (Puig et al., 2004b) and

in Nazaré Canyon. The data collected at the head of Halibut Canyon suggest the occurrence of the same process, although the sampling interval of the OBSs was too long (60 min vs. the 5 min interval used by Gardner in Baltimore Canyon) to clearly depict the internal wave resuspension mechanism, and only the bursts that coincided in time with the passage of the internal bore captured the
observed SSC peaks.

Based on the coarse surface sediment at the deployment site, these particles seem to have been resuspended from deeper parts of the canyon, where surface sediments are much finer. Comparing the temperature drop down to ~5 °C at the time of the passage of the internal tidal bore and the data from the historical CTD profiles, we can estimate that the water was coming from around 500–600 m depth, suggesting a vertical internal tide excursion of ~200 m.

The low SSC measurements recorded during the down-canyon gravity flows indicate that their increased density cannot be explained by large amounts of sediments in suspension, while the decrease in temperature observed in the records presumably corresponded to the formation of cold dense waters over the shelf that eventually cascaded into the canyon head. Unfortunately, no conductivity measurements were available on RALPH during this deployment to determine the density of the seawater at the time of the gravity flows. However, this interpretation is supported by the fact that the gravity flows were recorded during or immediately after periods of cold air temperature and sustained heat loss that could trigger convection and eventually increase the density of the near-bottom shelf water.

4.3 Method

All studies which have been dealt with sediment transportation mechanisms have used various methods for data retrieval and analysis such as below which used at Canada.

4.3.1 RALPH

One used method is the RALPH equipment which was applied at Halibut Canyon, eastern Canada margin and will be present below.

As part of the ‘Nearbed Wave and Current Forcing and Sediment Dynamics’ project at the Geological Survey of Canada, the bottom boundary- layer quadrapod RALPH was deployed during winter 2008–2009 at the head of Halibut Canyon, downslope of Halibut Channel, at a depth of 276 m. The continental slope in this region is cut by a dendritic system of deep canyons with sharp intercanyon ridges. More precisely, RALPH was placed in the head of the western branch of Halibut Canyon, here informally termed West Halibut Canyon. The heads of these canyons are approximately at 150–200 m below sea-level, canyon walls are steep (up to 40°)

and gullied, and canyon widths vary between 1.5 and 4.0 km. Deeper downslope across the margin, Halibut Canyon, Haddock Canyon and Green Canyon coalesce into Grand Banks Valley at 2500 m depth.

RALPH is an autonomous bottom boundary layer quadrapod frame equipped with various sensors for observing and recording hydrodynamic and sediment-transport parameters on the seafloor such as waves, currents, turbulence, suspended sediment concentration, and bedforms. The sensors mounted on the quadrapod during this deployment, and their heights above the seafloor and sampling strategy are listed in below table.

List of sensors mounted on the quadrapod RALPH during the winter 2008–2009 deployment at the head of the West Halibut Canyon with sampling strategy and heights above the seafloor.

Sensors	Sampling strategy	Height above bottom
RALPH pressure transducer (500 psi)	30 min burst at 2 Hz every 60 min	156 cm
RALPH compass	30 min burst at 2 Hz every 60 min	152 cm
RALPH tilt/roll sensor	30 min burst at 2 Hz every 60 min	152 cm
6 D&A optical backscatter sensors (OBS)	30 min burst at 2 Hz every 60 min	13, 34, 52, 72, 92, 111 cm
2 Alec electromagnetic current meters	3 min burst at 1 Hz every 60 min	30, 50 cm
Nobska travel-time current meter	15 min burst at 2 Hz every 60 min	100 cm
Mesotech 1 MHz acoustic backscatter sensor (ABS)	3 min burst at 4 Hz every 60 min	132 cm (1 cm cell size)
Nortek 2 MHz ADCP (downward looking)	1 min profile at 1 Hz every 3 min	130 cm (15 cm cell size)
RDI 300 kHz ADCP (upward looking)	1 min profile at 1 Hz every 3 min	175 cm (4 m cell size)
Sony HD-SR8 Camera (downward looking)	10 s clip and 1 photo every 30 min	133 cm

Figure 27 List of sensors mounted on the quadrapod RALPH during the winter 2008–2009 deployment at the head of the West Halibut Canyon with sampling strategy and heights above the seafloor.

RALPH was deployed on 12 December 2008 and recovered on 11 March 2009, but data collection was planned for only one month and the duration of the various time series was limited by battery capacity or instrument failures. The main RALPH logger, which controls the pressure, compass, tilt-roll and optical backscatter sensors (OBS) lasted 20 days. The 1 MHz acoustic backscatter sensor (ABS), which was also controlled by the main RALPH logger, lasted only 10 days due to a data storage issue. The Nobska travel-time current meter and the Nortek 2 MHz downward-looking acoustic Doppler current profiler (ADCP) logged 33 days. The

Teledyne RDI 300 kHz upward-looking ADCP recorded for 37 days. The downward-looking camera collected images during 89 days, covering the entire deployment.

The downward-looking ADCP successfully recorded profiles of 1-minute-mean velocity in 10 bins every 3 min. The bin size was 15 cm and only the first 6 bins provided valid data due to interferences of the sea floor in the remainder. The upward-looking ADCP also recorded profiles of 1-minute-mean velocity every 3 min in 35 bins of 4 m, covering half of the water column, from approximately 270 m water depth (i.e. 6 m above the bottom) to 130 m water depth (i.e. shelf-break depths). Some of the velocity profiles, however, did not meet the criteria for good quality in the bins furthest from the transducer head because of a low signal-to-noise ratio. This is not uncommon for these types of acoustic profilers that depend on sufficient numbers of scatterers in the water column to produce a return signal.

The single point velocimeters mounted on the quadrapod (i.e., the 2 stand alone Alec electromagnetic current meters and the self-contained Nobska current meter) sampled in burstmode at 1 and 2 Hz respectively, and the recorded data was averaged hourly.

RALPH's bottom-looking camera showed that the surface sediment within the canyon head was a mixture of sand and gravel partially covered by finer sediments. However, bulk samples were not taken at the deployment site for calibration purposes. Instead, OBS and ABS were calibrated in the laboratory using sediments with similar granulometric characteristics to provide suspended sediment concentrations (SSC). The isolated spikes in the OBS records that were not observed simultaneously in all devices were removed from the series. These spikes were attributed to interferences of the optical measurements by living organisms (fish and shrimps), which were observed in most of the video footages.

In situ temperature was recorded independently by all five velocity sensors mounted on the tetrapod and also by RALPH's internal thermistor, which unlike the others was not in direct contact with seawater.

Wind and wave conditions in the study area during the deployment period were recorded by two buoys from Environment Canada. Buoy C44251, located on Nickerson Bank in 71 m water depth off the south Newfoundland coast, and buoy C44138, located on the continental slope southwest of The Grand Banks in 1500 m water depth. Wind speed and direction, significant wave height, air temperature and sea surface temperature parameters were obtained directly from the standard meteorological data file. The sensible heat flux was computed from the buoy measurements (wind speed, dry-bulb air temperature, air pressure and sea surface temperature) using the MATLAB® air-sea toolbox. The latent heat flux could not be calculated properly due to the lack of relative humidity measurements on the buoys.

A hydrographic (i.e., CTD) profile was conducted at the time of RALPH deployment to characterize the properties of the water column within the canyon. Unfortunately, due to the fact that the recovery cruise took place on a vessel of opportunity, no CTD cast was conducted at the time of the instrument retrieval, which was almost two months after the time series record elapsed. Additionally, historical hydrographical profiles from the Grand Banks shelf south and east of Newfoundland, including the region of Halibut Channel and upper Halibut Canyon, were retrieved from the data inventory from Fisheries and Oceans Canada Integrated Science Data

Management (ISDM) to determine the typical water properties of the study region during winter and their evolution throughout time.

4.3.2 Multibeam bathymetric data

Subject method will be presented with below appliance on activity of the Pointe-des-Monts submarine canyons which was assessed by using two sets of high-resolution multibeam bathymetric data.

The first dataset was acquired in 2007 by the Canadian Hydrographic Service (CHS) with a Kongsberg EM-1002 multibeam echosounder (95 kHz) between 20 and 350 m water depth (3 m-grid) on board the F.G. Creed. The second dataset was acquired in 2012 with 1) a Kongsberg EM-2040 at a frequency of 300 kHz on board the R/V Coriolis II (1 m-grid) at depths of 20–350 m and 2) a Reson Seabat 8101 (245 kHz) at depths of 5–20 m (3 m-grid) on board the R/V Louis-Edmond-Hamelin. A DGPS was used in each case, so the horizontal uncertainty does not exceed 2 m. The vertical uncertainty of the two echosounders is typically less than 0.1 m. However, the vertical uncertainty between the two datasets is greater for different reasons: 1) Tidal variations were not collected during the surveys and are based on corrected tidal variations recorded at Rimouski by the CHS (co-tidal zone 00515 for Pointe-des-Monts); 2) The two multibeam echosounders have different numbers of beams (111 for the 2007 survey against 400 for the 2012 survey) and different beam width (2° × 2° for 2007 against 1° × 1° for 2012), which can lead to vertical differences, especially on steep slopes; 3) Slopes in the region are steep and can also lead to vertical errors if the navigation is off by 1 or 2 m; 4) Alignment and offset errors of both surveys; 5) Refraction residual errors due to the complex water density change in the LSLE. The 2007 bathymetric data was also processed for a 15 m grid resolution by the CHS. Theywere able to produce a 3mgrid but vertical precision is diminished, limiting the fine-scale analysis of vertical changes in this study. For these reasons, spatial changes (x, y) were also analyzed when depth differences were important in order to validate them.

Grain-size analysis on three samples collected in the Pointe-des- Monts region was performed using a Horiba LA-950 laser diffraction particle size analyzer. Samples were diluted in a calgon solution and shaken, then submitted to an ultrasound bath. The grain-size distributions and mean grain size are presented in this paper.

The physical oceanographic conditions prevailing offshore Pointedes- Monts were examined with a three-dimensional coupled sea ice– ocean model for the Gulf of St. Lawrence developed by Saucier et al. (2003). The 2007–2012 water density and maximum vertical kinetic energy density from the 5 km grid over the submarine canyons region were extracted from the model and used as indicators for internal motions. Idealized two-dimensional nonhydrostatic numerical simulations comparable to those described in Bourgault et al. (2013) were also carried out in the Pointe-des-Monts area in order to assess the shoaling effect of nonlinear high-frequency internal waves in the sector. For this idealized simulation, the background flow is quiescent and the background density profile (in kg/m3) is set to $\rho = 1029.7 \exp[0.4/(z + 52.5)]$ (with the vertical axis z being positive downward) which represents a climatological profile for the LSLE.

Internal waves were also characterized from satellite data. This was based on an analysis of the band 5 (1.55–1.75 μm) of Landsat TM sensor, which have been used to detect solitary and non-linear internal waves in other coastal zones (Artale et al., 1990). Here, a Landsat-5/TM image collected on 15May 2006 over the study area was obtained from the U.S. Geological Survey EarthExplorer web site (L1G). The total radiance in Band 5 (in DNs) was enhanced to maximize the contrasts over the water body, which is mainly due to specular reflection of the sky radiance and/or the direct sun beam at the air–sea interface, known as sunglint. Sunglint depends on the sun and sensor viewing geometry and the wave facette geometry (Cox and Munk, 1954). Internal waves were outlined on satellite imagery by the changes in surface roughness and the bands of calm water between different internal wavetrains (e.g., Pomar et al., 2012).

CHAPTER 5
MEDITERRANEAN SEA

5.1 STRUCTURAL BACKGROUND OF THE MEDITERRANEAN

After a complex tectonic history of thrusting and rifting involving the Eurasian, African, and Arabian plates, the northward motion of Arabia finally closed the link between the eastern parts of the Mediterranean and the remnants of the Tethys Ocean in the late Miocene, around 9 million years ago. From this time onwards, the Mediterranean developed the enclosed basin physiography that is seen today.

The Mediterranean Sea is a geologically active region as shown by its seismic and volcanic activity, and the uplift of present-day landmasses. The landscape thus continues to develop in a highly dynamic manner, which has important consequences for this region's continental margin. Some of the main geological structures in the Mediterranean are clearly reflected in its present seafloor morphology.

5.2 OVERALL PHYSIOGRAPHY OF THE MEDITERRANEAN

The Mediterranean Basin occupies an area of almost 2.6 million km2, with an average water depth of approximately 1,500 m. The Mediterranean Sea is composed of a series of small basins (Figure 28) involving a large number of continental fragments. These basins, which are very different in terms of dimensions, physiography, and geologic evolution, can be grouped into western and eastern sets, separated by the relatively shallow Strait of Sicily. The Black Sea is an isolated basin adjacent to the eastern Mediterranean Sea.

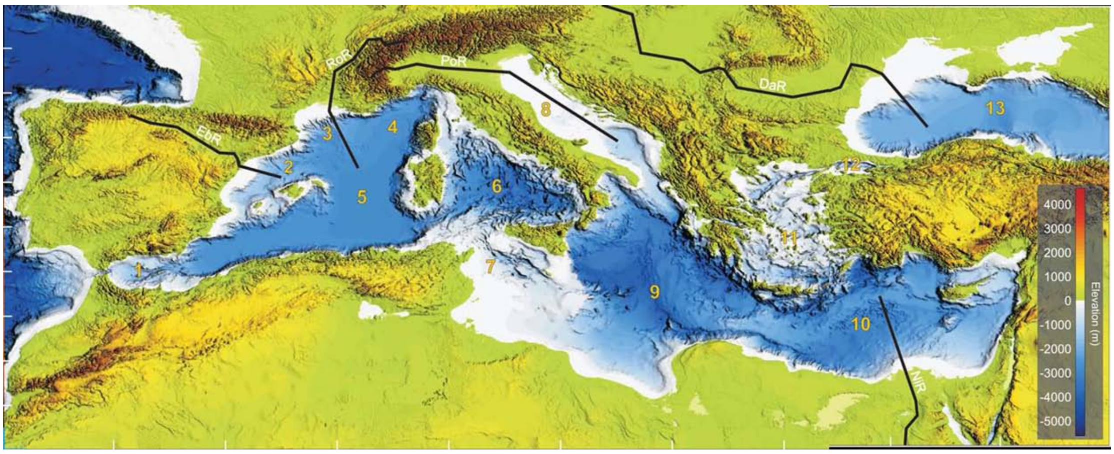


Figure 28 Mediterranean overview

5.2.1 Western Mediterranean

The western Mediterranean has an area of approximately 0.9 million km2, and it includes the Alboran Sea, the Algerian- Balearic Basin, the Catalano-Balearic Sea, the Gulf of Lions, the Ligurian Sea, and the Tyrrhenian Basin. At the westernmost end of the western Mediterranean area there is the only connection of the present Mediterranean Sea to the global ocean through the Gibraltar Strait. This passage, only 14 km wide, exerts an important control on the water circulation in the Mediterranean Sea and has largely determined its singularity.

The continental shelves tend to be narrow off the southern and northern Iberian Peninsula, the Balearic Islands, Corsica, Sardinia, the western Italian coast, northern Africa, and the Maritime Alps, where mountain slopes drop almost straight into the sea. Larger continental shelves, more than 50 km wide, are present off the Ebro and Rhône Rivers mainly due to the progradation of deltaic systems. The continental shelf off the north of Tunisia is also wide, but in this case, it is because of structural control. Bathyal plains occupy large areas in the western Mediterranean. These are located between the Balearic Islands, north of Africa and Sardinia with depths reaching 2,800 m, and in the Tyrrhenian basin with depths up to 3,430 m. These bathyal plains formed during the thinning of continental crust that took place in the rifting phases when the Balearic Islands, Corsica, and Sardinia rotated away from the Eurasian continent, and the Tyrrhenian Sea opened.

5.2.2 Eastern Mediterranean

Conversely, the eastern Mediterranean has a highly varied physiographic character. It includes the Strait of Sicily, the Adriatic Sea, the Ionian Sea, the Levantine Basin, the Aegean Sea, and the Marmara Sea. The eastern Mediterranean occupies an area of approximately 1.7 million km2. These seas and basins are underlain by oceanic crust under their main area, and thinned continental crust below their peripheries. This sector is more difficult to describe in terms of physiography than the western basins. There are important tectonic structures that determine the morphology and development of the basins. The main structures clearly visible in the bathymetry of the eastern Mediterranean are the Hellenic Trench and the Mediterranean Ridge. The Hellenic Trench is a subduction zone reaching a maximum depth of 4,661 m to the west of Crete and represents the deepest point in the Mediterranean. This trench confines the Aegean Sea to the north, arching from the western Peleponnese to southeast of Rhodes Island, which lies southwest of the Anatolian Peninsula. The Mediterranean Ridge runs parallel to this structure, from the Ionian Basin to the west, to the Cyprus arch to the east. This 1,500-km-long structure represents a huge wedge-shaped tectono-sedimentary body emplaced as a consequence of the Africa-Aegean plates convergence.

The continental shelves in the eastern basin are narrow off Peleponnese, Crete, and southern and northern Turkey. However, they are well developed particularly to the east of Tunisia, in the area directly under the influence of deposits from the Nile River delta, and in the Adriatic, where large portions are shallower than 100 m (Figure 29). The Aegean Sea is also relatively shallow, a result of its relatively young crust rather than high sediment input. Basin floors are deeper, but smaller, than those in the western basin. Maximum depths are up to 4,200 m in the Ionian Abyssal Plain and 3,200 m in the Herodotus Abyssal Plain.

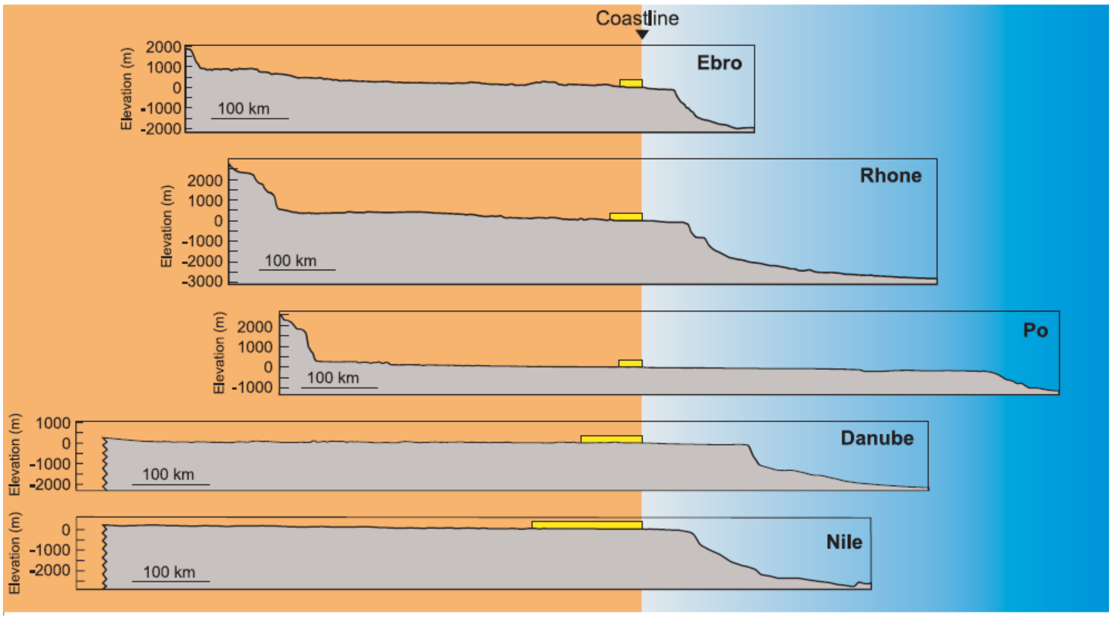


Figure 29 Topographic profi les along the main river systems of the Mediterranean, from catchment areas to the deeper parts of the associated continental margins.

5.2.3 Black Sea

The Black Sea is an inland sea segregated from the eastern Mediterranean, connecting only to the Bosphorus Strait and the Marmara Sea. Its floor, with depths up to 2,130 m, is shallower than those observed in the Mediterranean. The continental shelves are narrow on the Black Sea's southern margin, and due to the Danube River's influence, are wide on its northern margin.

5.3 MEDITERRANEAN CANYONS: AN OVERVIEW

According to a global survey, were identified 518 submarine canyons in the Mediterranean Sea with a depth range in excess of 1000 m, a width/length ratio less than 150:1 and a depth incision in excess of 100 m, as part of a world total of 5849 large canyons. This figure is to be compared with the area and the volume (~3.85 Mkm3) of the Mediterranean Sea with respect to the global ocean (~362 Mkm2 and ~1,335 Mkm3, respectively). In other words, while only representing the 0.7% of the area and 0.3% of the volume of the world's oceans, the Mediterranean Sea contains 8.85% of the submarine canyons. Canyons in the Mediterranean Sea are also most closely spaced (14.9 km only) and more dendritic (12.9 limbs per 100,000 km2) than in any other geographic region. These simple data highlight the relevance of submarine canyons in the Mediterranean Sea and points to their significance for the functioning of this land-locked basin.

As we have mentioned sub-divided large submarine canyons into three main types, in order to study their geomorphic differences between active and passive continental margins on a global scale:

Type 1

Shelf-incising canyons having heads with a clear bathymetric connection to a major river system

Type 2

Shelf-incising canyons with no clear bathymetric connection to a major river system

Type 3

blind canyons incised onto the continental slope.

In below image (Figure 30) is appeared the distribution of these three types around the Mediterranean Sea.

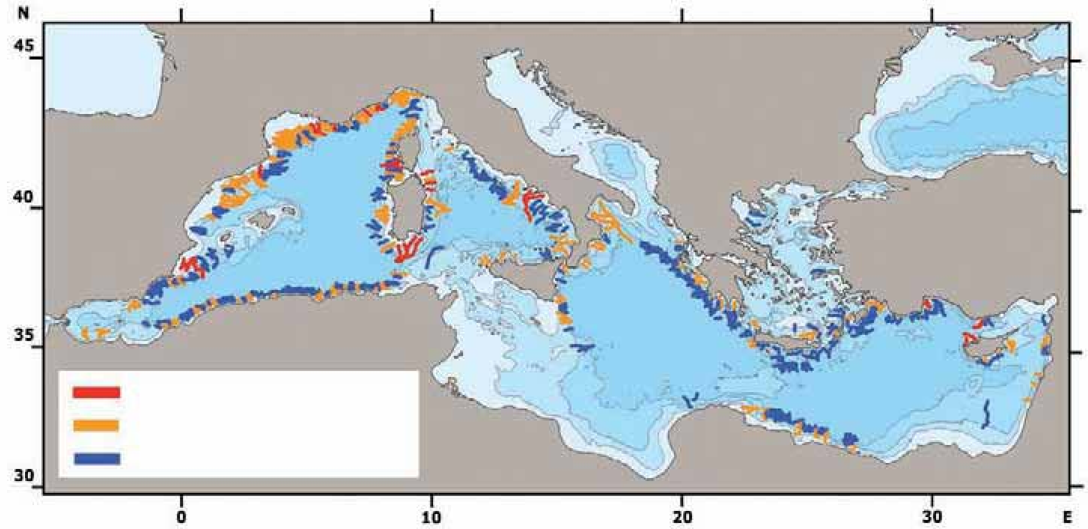


Figure 30 Canyon type distribution. Red Type1, Yellow Type 2, Blue Type 3

5.4 Comparison of western and east area

A recent systematic detailed bathymetric mapping of the Mediterranean continental margins and deep basins has made it possible to highlight strong contrasts between various submarine canyon networks cutting across the Western and Eastern Mediterranean continental slopes.

5.4.1 The Western Mediterranean

Along the Western Mediterranean continental slope, we can distinguish several areas characterized by strongly contrasted canyon morphologies, even if parts of this contrast can be referred to differences in the availability of precise bathymetric data; it clearly appears that the most important and widespread canyon systems are observed along the northwestern Mediterranean Sea continental slopes.

Along the northern coasts, and from West to East, we first distinguish a network of canyons running across the Gulf of Valencia and Catalonia slopes, and merging at depth into a meandering channel through which most of the Ebro sediments are transported into the abyssal plain. From the Pyrenean borders to the vicinity of Marseille, the Gulf of Lion is itself characterized by numerous canyons cut into a thick Pliocene and Quaternary sedimentary blanket deposited by the bordering rivers and particularly the Rhone. Available seismic data show that most of these canyons are, however, superimposed on former submarine/ sub-aerial valleys created during the Messinian Salinity Crisis (roughly between 6 and 5 My ago), when the sea level dropped by more than 1200/1500 m as a consequence of the closing of the oceanic connections between the Mediterranean and the Atlantic. These canyons, being entailed into relatively unconsolidated sediments show drastic morphologic and hydrologic regime contrasts with the Catalonia canyons, but are comparable to most of the canyons off Valencia, also cut into thick, soft sediments. The meandering canyons and deep sedimentary channels seen along the Gulf of Valencia and Gulf of Lion continental margins thus participate in the sedimentary drainage mechanism towards the deep surrounding basins. Further East, from Marseille to Genova, the canyons, also mainly inherited from the Messinian low stand sea level (and subsequent aerial erosion), cut across various geological formations consisting either of massive limestone (east of Marseille), metamorphic, volcanic rocks (from Toulon to Frejus) or various alpine tectonic units (from Cannes to Genova). Most of these basement rocks are often directly exposed on the seabed.

A comparable setting characterizes western Corsica, and probably the western continental slope of Sardinia, where the Messinian erosion may have been superimposed on previous canyon features inherited from the formation of the continental slope, some between 25 and 11 My during the rifting of a subsequent opening of the Western Mediterranean basin; today the majority of these canyons appears almost devoid of sediments, while along the eastern margin of Corsica the canyons drain most of the erosion products towards the Corsica channel between the Corsican mainland and island of Elba. Except along part of the Sardinia and North Sicily margin and off western Calabria, we cannot observe significant canyons around the Tyrrhenian Sea; this is probably due to the very recent age of this basin, which formed only in the last 5 to 1 My, and the majority of whose continental slopes were thus not subjected to the Messinian crisis or aerial erosion.

By opposition to the northern Mediterranean Sea margins, the North African margins exhibit only short and sub-linear canyons, deeply imprinted on a quite narrow, geologically active, and probably uplifting, continental slope. Moreover the onshore drainage system consists mainly of short-lived rivers without regular water supply.

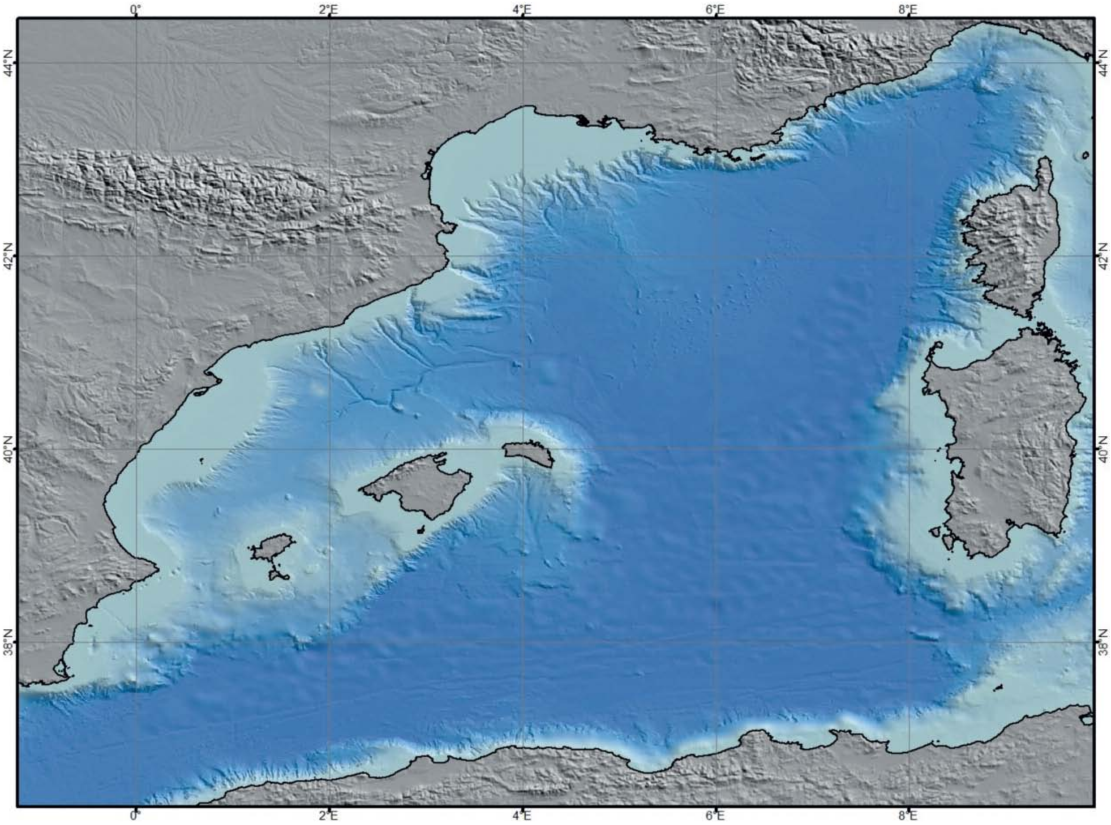


Figure 31 The highest density of Mediterranean submarine canyons is found in the northwestern Mediterranean

5.4.2 Eastern Mediterranean

Around the Eastern Mediterranean Sea, only the Calabria, Cyrenaica and Western desert (Western Egypt) continental slopes show significant canyon networks.

Off Calabria, and as a consequence of the virtual absence of a continental shelf, the few existing canyons are directly connected to small mountain-supplied rivers and are subjected to strong erosion, itself the consequence of an active general coastal uplift. Only a few significant canyons can be observed West of the Peloponnese, South of Crete and Turkey and off the Levantine coasts. Little is known on these canyons also located in active tectonic areas. Relatively numerous short canyons can be observed off Cyrenaica and the Western desert (Egypt). We believe that most of these features originated during the Messinian low stand but, not being connected with any aerial drainage system, they probably did not evolve since that time, except maybe during various pluvial periods in Quaternary times. Off the Nile delta, the Egyptian continental margin shows a rather specific case where today a unique and wide canyon can be seen just at the mouth of the Rosetta branch of the Nile river; this canyon, the Rosetta canyon, feeds a complex turbidite and meandering channel system, through which most of the erosion products and nutrients originating from the Nile drainage are dispersed into the deep Herodotus abyssal plain several hundred kilometers away from the coast line. The presentday Rosetta canyon is the last morphological expression of various similar canyons cut by the Nile River since the Lower Pliocene (5 My) but now deeply buried below the Quaternary deltaic deposits.

With the exception of a few short canyons in tectonically active areas, such as in the Marmara Sea and North Anatolia trough (North Aegean), no significant canyon can be observed within the shallow Aegean Sea.

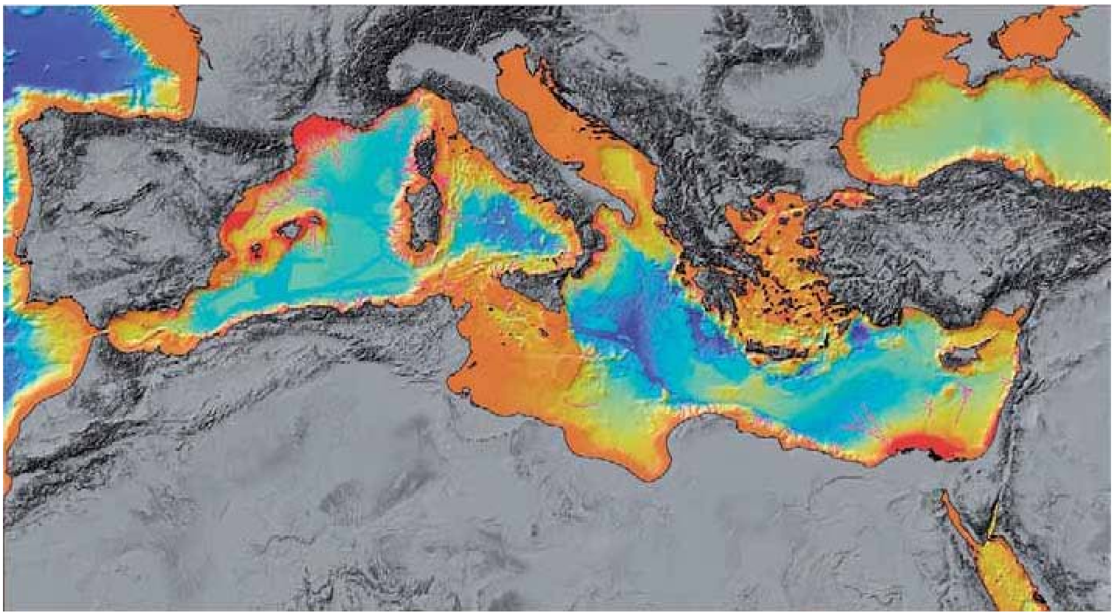


Figure 32 Morpho-bathymetry of the Mediterranean Sea showing the main canyon and channel systems around the basin.

5.4.3 Two representative examples

Two basic examples are mentioned below: the northern Ligurian margin in the Western Mediterranean, and the Nile deep-sea fan in the Eastern Mediterranean. These two areas are different in terms of canyon morphology, evolution through time and number, and in terms of the tectonic and climatic context of formation.

The northern Ligurian margin

Along the northern Ligurian continental margin, the continental shelf width ranges from a maximum of 2 km to less than 200 m at specific locations, as along the "Baie des Anges" in front of the city of Nice. The shelf break is located quite close to the coastline, at an average of 50-100 m water depth, but could be shallower, i.e. less than 20 m of water depth, as in front of Nice airport. The continental slope is steep and extends over no more than 20 km to a water depth of 2000 m with an average angle of 11°. The base of the slope is characterized by a sharp decrease in the slope angle, to less than 3°. In the deep part of the basin (2600 m of water depth), the bathymetric gradient decreases to 1° or less. The marked steepness of the continental slope is partly explained by a tectonic inversion of the margin implying reactivation of inherited transverse structures and development of new faults. Such tectonic reactivation is believed to be responsible for the uplift of the margin which is evidenced by the deformation to the north of the Messinian erosional surface. Uplift is particularly pronounced off the city of Imperia (Italy). Reactivation is also responsible for an enhanced activity of gravity processes on the continental slope.

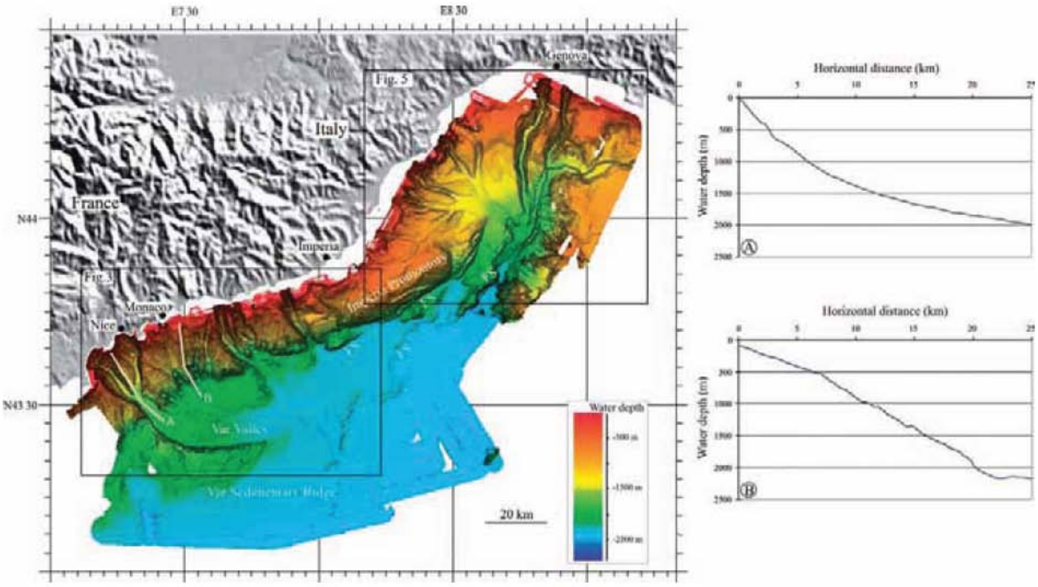


Figure 33 Shaded bathymetric map of the northern Ligurian margin.
A is an example of a concave-up topographic profile as observed in the Var-Paillon canyon area.
B is an example of a convex-up topographic profile as observed in Roya-Nervia-Taggia canyon area.
FS is Fault Structure.

Small mountain-supplied rivers feed the western Ligurian margin; they are, from west to east, the Var, Paillon, Roya, Taggia and Argentina Rivers. On land, the rivers drain catchments that are usually 200-300 km2 and consist of either metamorphic rocks or calcareous and marls formation. The Var River is an exception in terms of its catchment area: it forms in the Southern Alps, at an altitude of 2352 m and 120 km inland, and drains a basin of 2822 km2. All these rivers experience violent flash floods every year, during the fall and spring. The average water discharge of the Var River, about 50 m3/s, can increase tenfold during floods, and suspended sediment concentration can reach tens of kg/m3. From the rating curve of the Var River, it is estimated that hyperpycnal currents could be generated during river floods, with a return period of about 2 to 5 years. Such turbulent flows are generated at the river mouth when the density of fresh water transporting suspended particles exceeds the density of the ambient seawater. In the case of the Var River, a critical concentration of suspended particles of 40-44 kg/m3 and a critical river discharge ranging from 620 to 1250 m3/s are required to produce hyperpycnal flows.

Based on morphological characteristics of the present-day seafloor, the Ligurian margin can be divided in two western and eastern segments separated by a SW-NE trending ridge or Imperia Promontory. From the city of Nice (France) to the Gulf of Genova (Italy; Fig. 33), seventeen canyons can be identified along the continental slope. They are, from west to east, the Var, Paillon, Roya, Nervia, Taggia, Verde, Mercula, Laigueglia, Cuenta, Varatella, Pora, Finale, Noli, Vado, Polcevera, Bisagno and Levante Canyons. These canyons initiate either at a shallow water depth, directly at the mouth of some of the rivers feeding the Ligurian continental slope and basin, or at greater depth, along the outer continental shelf or even on the upper continental slope.

The Var, Paillon, Roya, Nervia, Taggia and Verde canyons cut the western margin segment, between Nice and Imperia. Most of these canyons initiate at very shallow depths (< 10 m) and connect directly to the mouth of the respective Var, Paillon, Roya, Nervia and Argentina Rivers. The Verde canyon initiates at a greater depth (about 130 m), at the transition between the outer continental shelf and upper continental slope; no river valley or river deposits, following the same direction as this canyon axis, have been identified on land. Most of these canyons are on average 500-m deep and 2-5 km wide. They exhibit a V-shaped cross-section profile, suggesting intense and active erosive processes, or a U-shaped cross-section profile associated with thick accumulation of sediments on both sides of the canyons and along their axis. This type of cross-section profile also correlates with the general along-axis longitudinal profile of each canyon. For example, the Var and Paillon Rivers exhibit a concave-up profile, suggesting they reached a “state of equilibrium”, and are mostly characterized by U-shaped profiles. The Roya, Nervia and Taggia canyons exhibit convex-up profiles suggesting that erosional processes must still be active within these canyons. They have not yet reached a state of equilibrium, and V-shaped cross-section profiles are predominant. Along the Verde canyon, the change from a U-shaped (upslope) to a V-shaped (downslope) profile attests to distinct dynamic behaviors occurring along a single canyon.

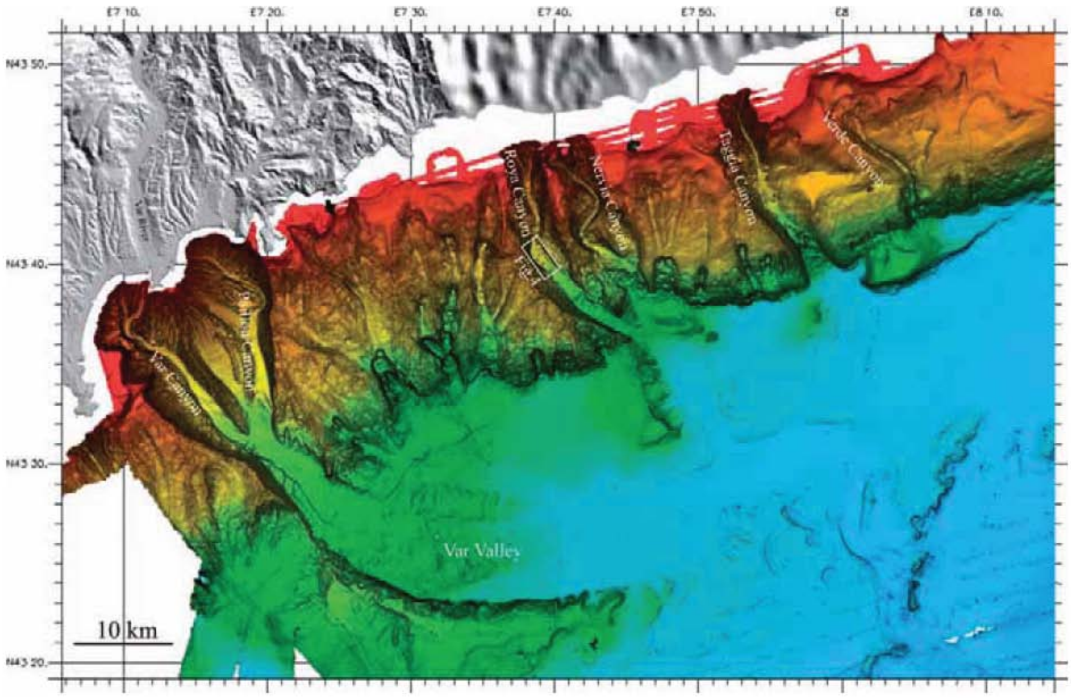


Figure 34 Shaded bathymetric map illustrating the morphology of the western Ligurian margin.

Several factors may explain these differences. The present day pathway of canyons is largely controlled by the pre-existing topography inherited from the Messinian erosive period:

(1) V-shaped canyons are located in pre-existing narrow valleys that channelized gravity flows within and along constricted conduits which increased their erosive power.

(2) U-shaped canyons developed in wider pre-existing valleys that allowed gravity flows to spread laterally, reducing their erosive power and favoring sediment deposition.

Faults that were active, at least during the Pliocene era, are associated with V-shaped canyons and were weakness areas that favored stronger erosion processes. Then, the uplift of the margin, mainly in front of Imperia during the Plio-Quaternary, caused a gradual increase of the continental-slope angle and a continuous change of its longitudinal topographic profile. Incision of canyons will thus increase to re-establish an equilibrium (concave-up) profile. Just after a modification of the margin topographic profile, erosion will first start at the base of the canyon and then propagate in an upslope direction. This could explain the increasing downslope erosion observed in the downstream part of the Verde canyon (V-shaped cross-section profile) as compared with the depositional pattern (U-shaped profile) characterizing its upstream sector. The Var, Paillon, Roya and Taggia canyons are still active nowadays in term of sediment transport. This is evidenced on side-scan sonar images by the absence of hemipelagic drape on the floor of their axis and the presence of coarse-grained (probably sand to boulder) accumulations such as dune-like structures (Fig. 35).

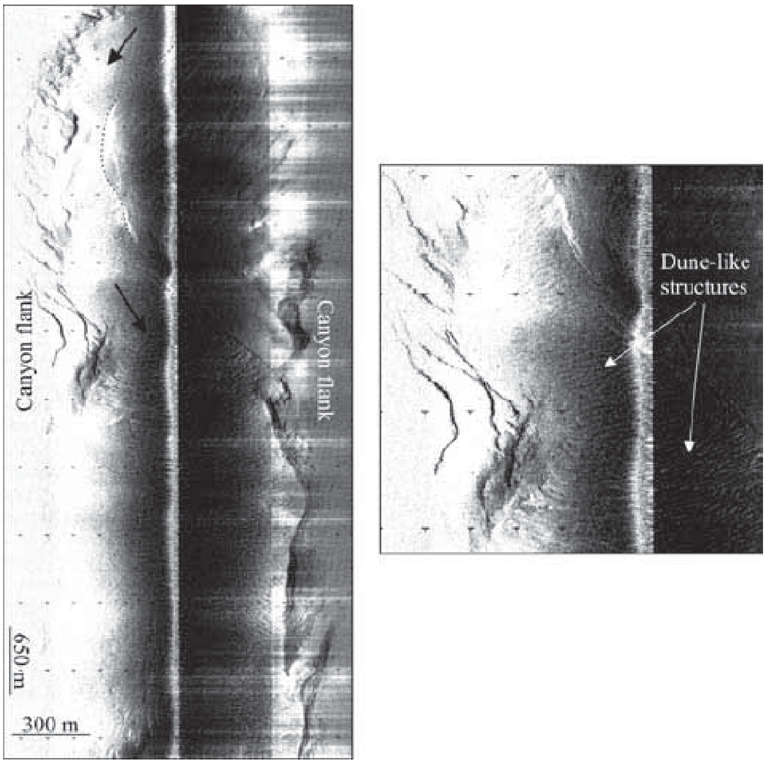


Figure 35 Side-scan sonar image obtained in the Roya canyon.

On the segment of margin comprised between Imperia and Savone, the network of canyons exhibits a SW-NE to W-E trend, i.e. oblique to the general margin trend (Figs 33 and 36). This unusual pattern is due to the presence of a tectonic ridge, the Imperia Promontory, and its progressive uplift during the Plio-Quaternary. In this area, the canyons are 50-m deep or less and 1-2 km wide. All these canyons exhibit a linear along-axis topographic profile, suggesting they have not yet reached their equilibrium profile and that erosion may be still active within their axis. Conversely, they exhibit a U-shaped crosssection profile which suggests depositional processes. In fact, seismic-reflection data collected perpendicular to the canyon axis document alternations between short phases of erosion and longer phases of deposition and vertical aggradations (Fig. 37A). Phases of erosion are associated with a lateral migration of the canyon axis. Such alternations between erosion and deposition are probably related to stages of uplift of the Imperia Promontory or to sea level fluctuations during the Quaternary era.

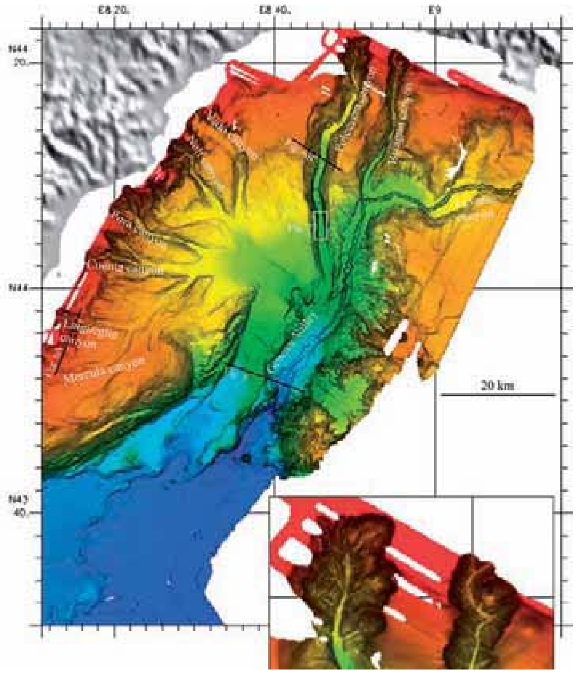


Figure 36 Shaded bathymetric map

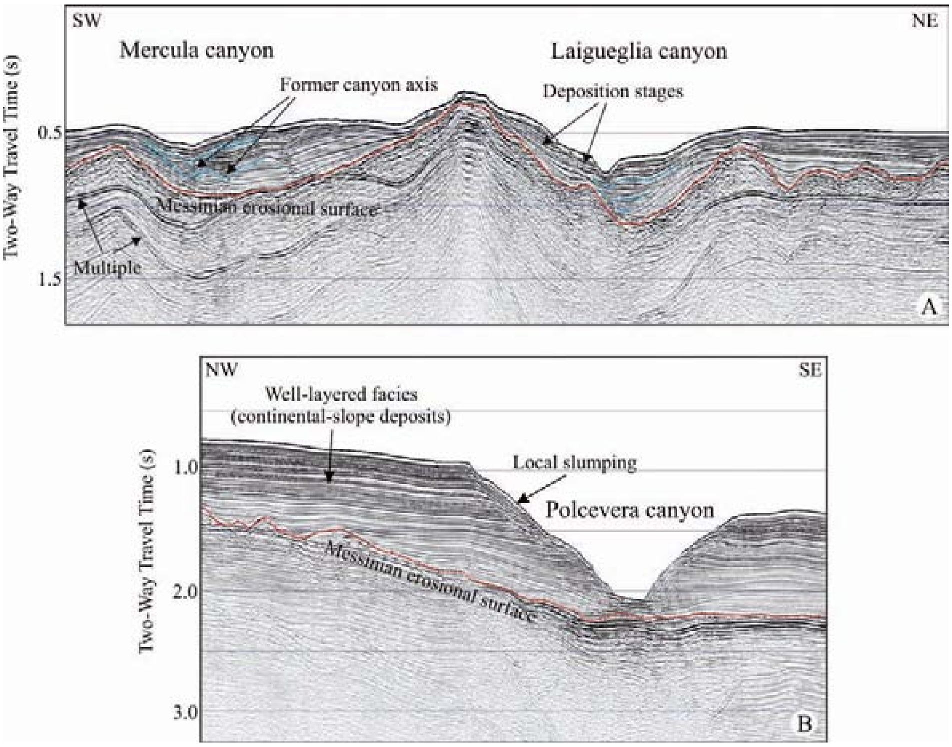


Figure 37 Seismic-reflection profiles illustrating the architecture of some of the canyons present along the eastern Ligurian margin.

The two largest canyons of the Ligurian margin lie offshore of Genova: the Polcevera and Bisagno canyons (Figs. 33 and 36). These features are more than 700-m deep, 20-km wide and about 60- km long. They are straight in the direction of the main slope angle. The two canyons exhibit a linear along-axis topographic profile, suggesting once more that erosive processes must predominate within their axis. They mostly exhibit a V-shaped profile along their pathway (Fig. 37B), confirming that erosion should be prevailing. Their steep walls are also strongly affected by landsliding processes (Fig. 37B). The present-day heads, which exhibit a well-developed cauliflower-like pattern (Fig. 36), incise the outer continental shelf and the upper continental slope. Such specific morphology results from the repetitive triggering of small-scale submarine retrogressive failures. Nowadays, the two canyons are not connected to fluvial inputs, though side-scan sonar images, collected within their axis, highlighted the presence of fresh erosional scours (Fig. 38). This suggests a recent activity of particle transfer. We thus believe that the local failure processes, affecting both the heads and flanks of the canyons, maintain the present-day activity of sedimentary processes and gravity flows within the canyons.

East of the Bisagno canyon, the Levante canyon exhibits first an east-west trend, then merges with the Bisagno canyon and finally pirates its main pathway. The Levante canyon, about 300- 400-m wide and 50-70-m deep, displays an unusual meandering plan-form pattern that usually corresponds to deep-sea turbidite channels. The three canyons coalesce downslope to form the 5-km wide and 400-600-m deep Genova Submarine Valley (Fig. 36). It exhibits a U-shaped cross-section profile and its pathway is clearly constrained by the presence of major faults bordering its right-hand side (looking down valley).

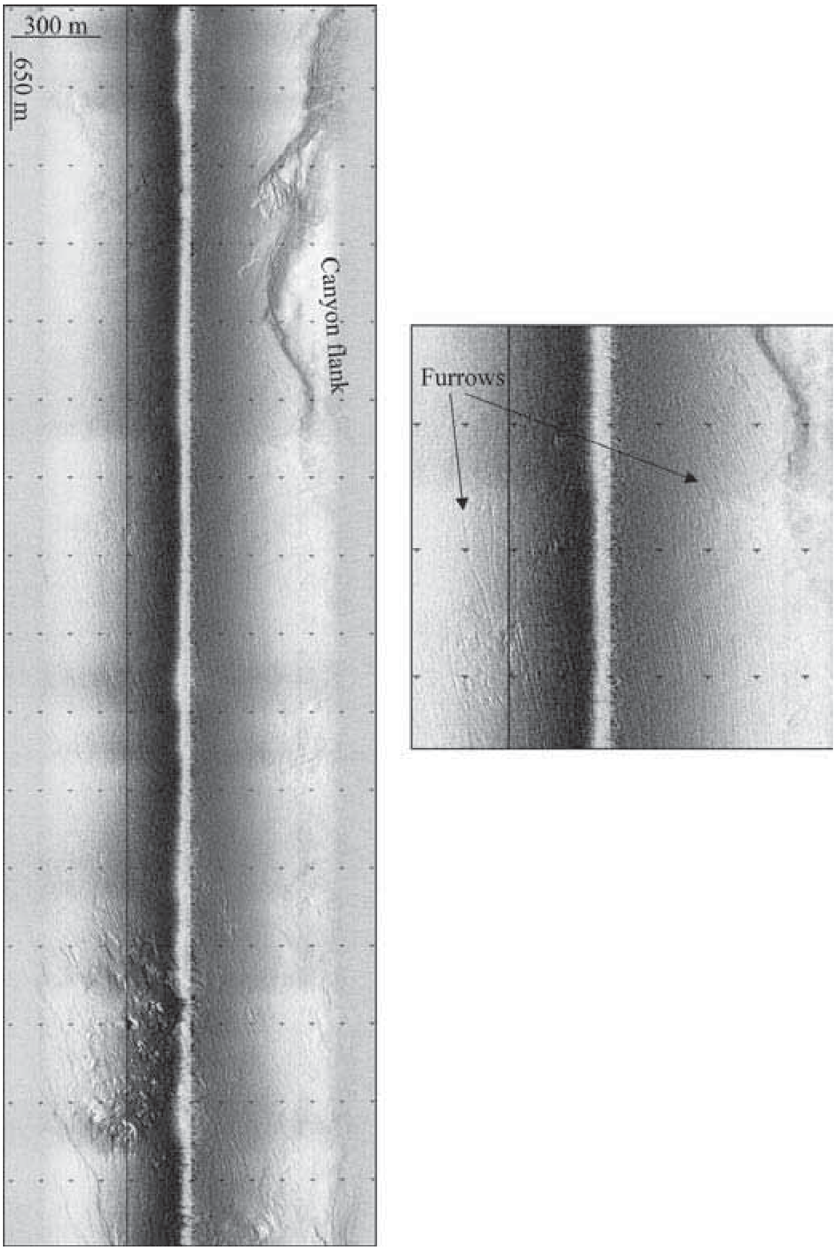


Figure 38 Side-scan sonar image obtained in the Polcevera canyon revealing the presence of abundant fresh furrows flooring the canyon.

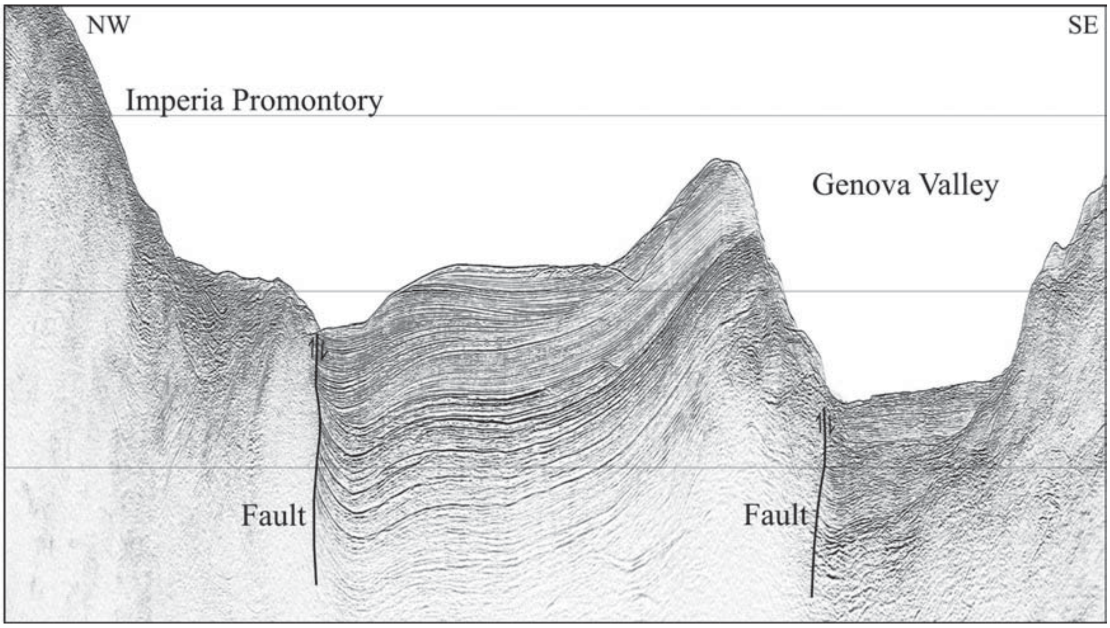


Figure 39 Seismic-reflection profile crossing the Genova Valley near the base of the continental slope

The Nile deep-sea fan

The Nile deep-sea cone (see Fig. 32) is the largest Plio-Quaternary silico-clastic accumulation of the Mediterranean Sea. The Nile River has delivered particles to the deep sea since the Messinian Salinity Crisis at least. The present-day Nile deep-sea fan, which built outwards over the Messinian evaporite, forms a 2000- 2500-m thick Pliocene and Quaternary sediment bulge. Offshore the Nile sub-aerial delta, the continental shelf widens from west to east from 30 to 60 km. The continental-slope angle is usually lower than 2°. Based on morphologic data, four main morphostructural provinces have been discriminated. A Western Province, located in continuity with the Rosetta branch off the Nile delta, is characterized by a dense network of turbidite channel-levee systems and large submarine landslides that repeatedly affected the upper continental slope. A Central Province displays small, progressive slope deformation of the uppermost tens of meters of sediments, and numerous pockmark fields. The base of the slope is itself deformed by salt-related faults. An Eastern Province contrasts with the two previous areas, as it is strongly affected by active salt tectonics that have generated normal faults on the upper slope, and large-scale folds at the base. In this area, channel-levee systems were built in relationship with the Damietta branch off the Nile River, but became inactive some 125,000 yrs ago. Finally, a Levantine Province is characterized by small-scale folding which deforms the Quaternary deposits, and by a few channellevee systems that can be observed up to the deep part of the basin, east and north of the Eratosthenes Seamount.

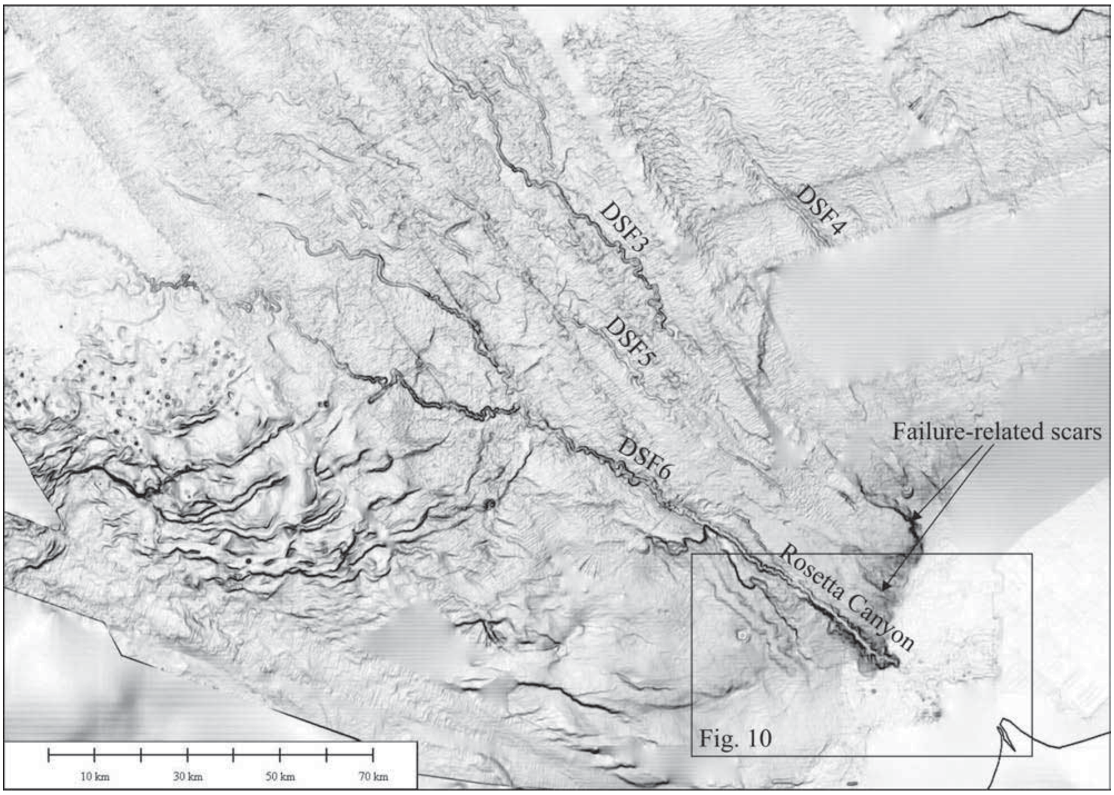


Figure 40 Slope-gradient map illustrating the presence of canyon, channel-levee systems and failure-related scars on the Nile continental margin offshore the Rosetta branch of the Nile subaerial delta.

In the western (or Rosetta) Province, four main channel-levee systems have been active during the last 115 ka. The oldest channel-levee system (DSF3; Fig. 40) initiated about ~115 ka (Marine Isotope Stage 5). A second channel-levee system (DSF4; Fig. 40) initiated at about 73-70 ka, at the end of the Saharan Pluvial period. DSF3 and DSF4 were active simultaneously during glacial stage 4 and inter stade MIS3 (73-50 ka). DSF3 finally became inactive around 50 ka and a third channel-levee system (DSF5; Fig. 21) was built. DSF5 became inactive during MIS2 (25-14.8 ka), whereas DSF4 had reduced activity. A fourth system (DSF6; Fig. 40) initiated during MIS3 at about 40 ka. DSF6 was active during the mid and late Termination I (14.8-10 ka) and during the early Holocene (10-~5 ka), while DSF4 had residual activity until about 10 ka. Except for the most recent one (DSF6), these channels are no longer connected to their feeding canyons which are probably buried or were reworked by mass-wasting events.

DSF6 is fed by the Rosetta Canyon (Fig. 40) located 30 km off the Rosetta branch mouth and breaching the upper slope through a 30-km wide scar induced by numerous slope failures. Rosetta Canyon, which initiates on the outer continental shelf at about 70 m water depth, (Fig 40), is about 25 km long and is straight in the main direction of the continental-slope angle. The canyon is about 200-250-m deep and narrows from 8 to 5 km downslope. The canyon head consists of imbricated semicircular scarps, 1 to 5 km wide, related to repetitive small-scale submarine failures which have merged into a typical cauliflower-like morphology (Fig. 40). Within the canyon, the longitudinal alongaxis topographic profile is rather linear but the whole DFS6, from the canyon head to its distal lobe (Herodotus Plain), exhibits a concave-up profile, suggesting that equilibrium conditions were reached. In cross section, the Rosetta Canyon is characterized by U- to poorly-developed V-shaped profiles where a large number of small-scale failures affected the canyon flanks (Fig. 40). Today the Rosetta Canyon is not directly connected to the Rosetta branch of the Nile, but connection could have existed during sea level lowstands, such as in the Last Glacial Maximum. Most of the gravity-flow deposits identified at the mouth of the DSF6 channels are thus thought to originate from failures triggered in the canyon head.

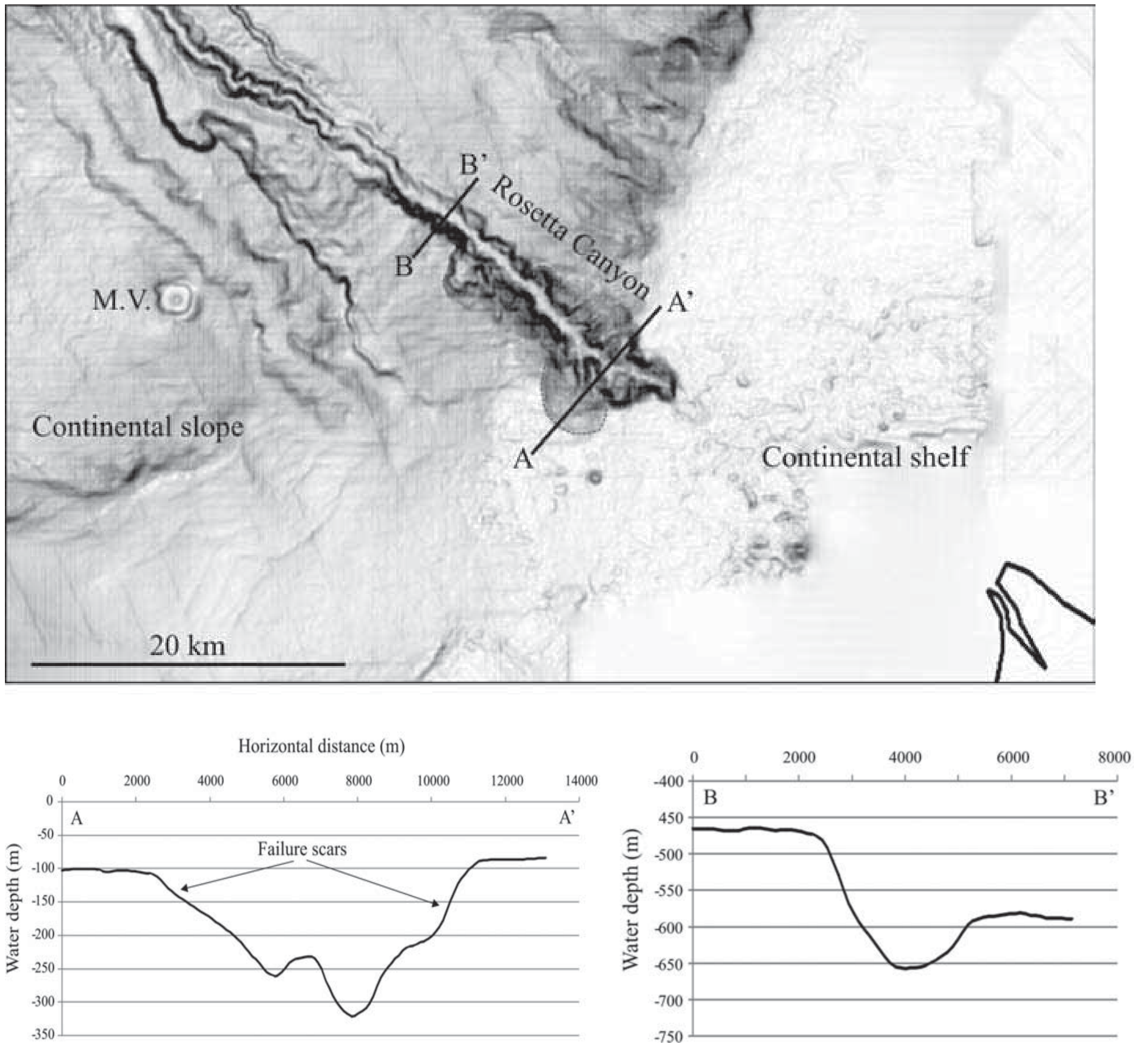


Figure 41 Slope-gradient map focusing on the Rosetta Canyon. M.V. is mud volcano. AA' and BB' are two cross-section topographic profilesof the Rosetta Canyon

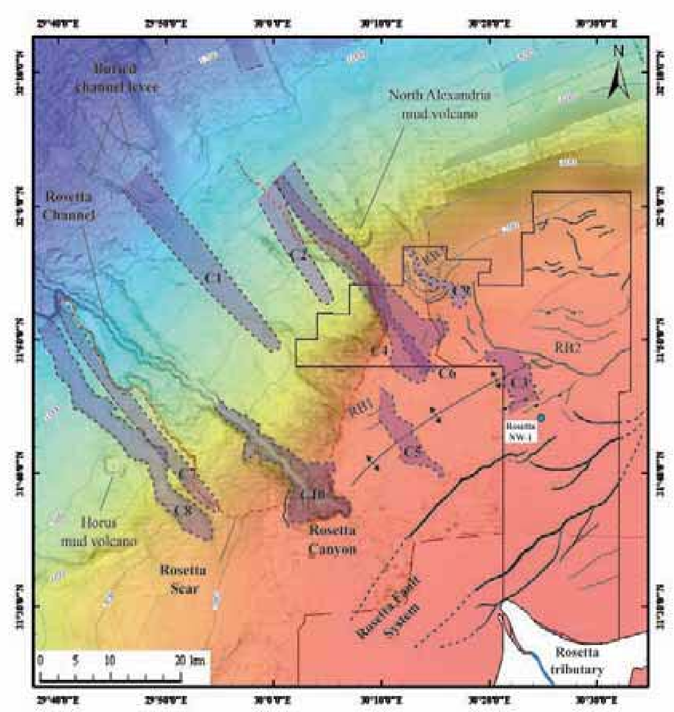


Figure 42 Bathymetric map illustrating the location of buried canyons offshore the Rosetta branch of the Nile delta

The use of 2D and 3D seismic-reflection data makes possible to identify nine additional buried canyons in the area which were built since the Upper Pliocene along a 55-km wide segment of the continental shelf and upper continental slope offshore the Nile Rosetta branch. These buried canyons lie at different stratigraphic levels suggesting a diachronous character. They have no, or little, expression on the presentday seafloor. They all trend SE-NO, except the oldest identified one which trends SSE-NNO (Fig. 42). The nine canyons exhibit different sizes, shapes, sinuosity, lengths of shelf incision (Fig. 40), emphasizing various processes of formation and evolution through time. Is described below a few canyons whose morphologies are representative of the entire set of identified canyons.

Canyon C3 (Figs. 39 and 40) is located within the upper Pliocene sedimentary section, at depths varying between 750-1200 m below the seafloor. Recognized over a distance of 9 km, this canyon is relatively straight and exhibits in cross section a U-shaped profile with a mean width of 3.5 km, and an axial incision varying between 200 and 350 m deep. Numerous semi-circular and imbricated scars, 0.2-1.5-km wide, affect its flanks (Fig. 41). C3 has incised the paleo-continental shelf over a distance of 6 km (Fig. 41).

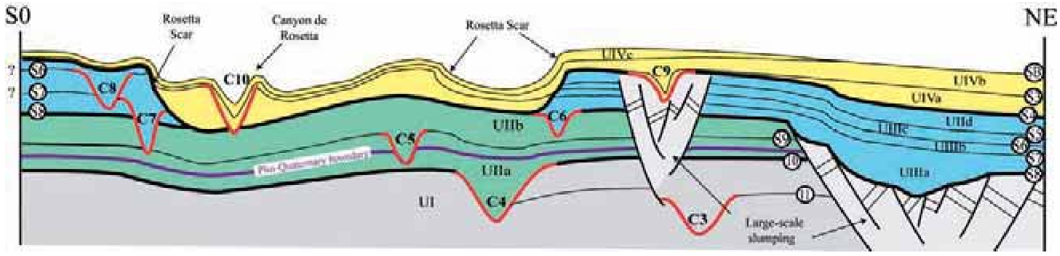


Figure 43 Schematic graphic section illustrating the stratigraphic location of the identified canyons offshore the Rosetta branch of the Nile delta

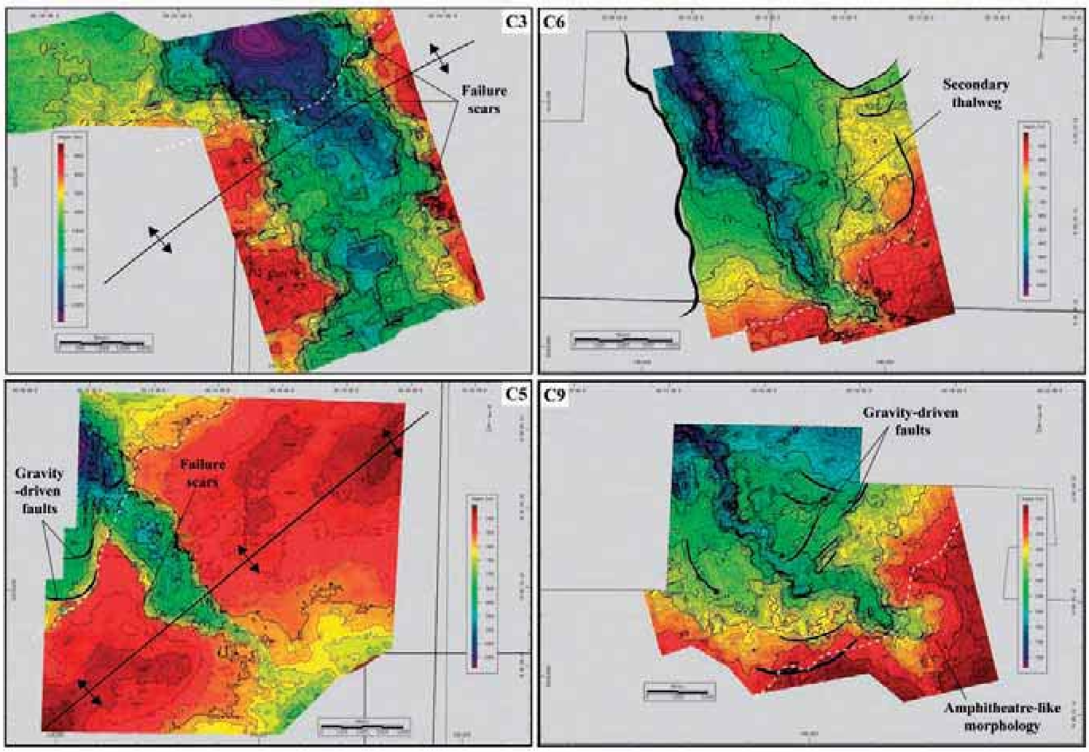


Figure 44 Maps of the basal erosion of canyons C3, C5, C6 and C9.
The white dashed line shows the location of the paleo-shelfbreak. Thick black lines represent fault escarpments

Canyon C5 is located between the present-day Rosetta Canyon and canyon C3. Mapped over a distance of 10 km, it is located at depths between 500 m and 1050 m below the seafloor, at the transition between the Pliocene and Pleistocene sedimentary sections. This canyon exhibits in cross-section a U-shaped profile and a longitudinal concave-up topographic profile close to the theoretical equilibrium profile. It is about 3-km wide, 120-m deep and shows a relatively straight plan-form pattern. Its width decreases from 3000 m to 500 m toward the continent, and its head has cut the paleo-shelf over a distance of more than 8 km (Fig. 41). A few semi-circular scars, 100-500-m wide, can be detected on the canyon flanks (Fig. 41).

Located north-east of the present-day Rosetta Canyon and canyon C5, canyon C6 is buried along the present-day eastern edge of the wide scar seen on the upper continental slope (Figs. 37 and 39). Mapped at depths between 550 m and 1050 m below the seafloor in the Quaternary cover, it extends over a distance of 12 km. Its head, characterized by numerous semi-circular scars (cauliflowerlike plan-form pattern), incised the paleo-shelf over a distance of at least 2 km (Fig. 41). The head gradually widens downslope, from 500 to 2000 m at the paleo-shelf break. Then, the canyon rapidly widens toward the basin to reach a width of 4 km (Fig. 41). The axial incision exhibits a V-shaped cross-section, 100-200 m deep, and is slightly sinuous.

Finally, buried canyon C9 is located about 10 km north-east of canyon C6. Mapped within the Quaternary section over a distance of 12 km and at depths between 250 and 800 m below the seafloor, this canyon has a head 1.5-km wide and about 250-m deep (Fig. 41) which also shows a typical cauliflower-like plan-form morphology due to coalescing semi-circular small scars (Fig. 41). C9, which has incised the paleo-shelf over less than 2 km, exhibiting a V-shaped cross-section profile and a well-developed sinuous plan-form pattern.

From these morphological analyses, one can distinguish two types of canyons: (1) canyons characterized by cauliflower-like heads restricted to the upper continental slope/outer shelf (C6, C9, Rosetta Canyon), and (2) canyons with a rather straight head incising the continental shelf towards the coastline over much longer distances (C3, C5). We believe that such differences reflect different processes of canyon formation where erosion could be constrained either by local processes of retrogressive failures located at the shelf break, or by more continuous downslope processes related to high-sediment discharges delivered at the mouth of the Rosetta branch.

In addition to these four canyons, buried canyons C7 and C8, which also cut across the Quaternary section, are located southwest of the present-day Rosetta Canyon (Figs. 39 and 40). Up until now, only the present-day Rosetta Canyon can be related with confidence to the most recent channel-levees system (DSF6) described by Ducassou et al. (2009). DSF6 initiated about 40 ka and was still active until 5 ka. Because of its stratigraphic position and its location and direction, we suspect that C9 could have been the source point for DSF4, active between 70 and 27 ka BP. Actually, C9 and the Rosetta Canyon may thus well have been active synchronously. The potential feeding canyons of DSF3 and DSF5 have not been yet identified. As they should be located within the 30-km wide scar affecting the upper continental slope, they may have been totally erased by the successive mass-wasting events that created the scar. This suggests that more canyons were likely to have existed during upper Pleistocene times.

All these canyons show some east-west and west-east phases of lateral migration which seem to be random. Each migration was probably sudden as no intermediate position of any canyon axis has been observed between two successive phases of canyon creation (Figs. 39 and 40). Such rapid lateral migrations are probably controlled by the migration/avulsion of the sub-aerial delta branches, each avulsion leading to a more or less instantaneous displacement of the main direction of particle fluxes towards the continental shelf and slope, and of the main depocenter location. The real timing of the activity of a single canyon remains impossible to estimate in the absence of specific stratigraphic data from drilling or coring. The correlation existing between the Rosetta Canyon and DSF6, and between canyon C9 and DSF4 suggests, however, a time span for each canyon activity in the order of about 35-40 ka.

5.5 THE FLUVIAL-DOMINATED SEASCAPES OF THE MEDITERRANEAN

Continental margins are affected by processes extending from sediment source to sediment sink or, in other words, from erosional to depositional areas. From this viewpoint the margin may be divided into different units that are interlinked by the flux of sediment: emerged lands, continental shelf, continental slope, continental rise, and basin floor.

Taking a general overview of the Mediterranean region topography we note that, apart from the deltaic zones of large rivers, the coastlines are mostly surrounded by mountain ranges (Figure 28). Only the coastal plains from eastern Tunisia to the Sinai Peninsula are free of mountains. The existence of surrounding mountains largely determines the seascape of the Mediterranean since it makes the basin boundaries very steep, thus impeding the development of settlements. In addition, the potential energy storage from mountainous areas makes the amount of erodible sediments very high. These sediments are then transported downslope by both permanent and non-permanent rivers, therefore contributing to the infill of this landlocked basin.

Locally modern-day sedimentation is dominated by organic-rich oozes, volcanic ashes, or aeolian sediments mostly coming from the arid areas of northern Africa. However, the seascape of the Mediterranean Sea is primarily related to its fluvial regime, aside of those areas dominated by neo-tectonics or volcanic processes.

There are few large rivers with well-defined coastal plains and deltas in the Mediterranean Sea. The most important ones from west to east are: Ebro, Rhône, Po, Danube, and Nile (Figure 29). These are perennial rivers supplied by very large hydrographical basins that in most cases collect water beyond the boundaries of the Mediterranean climatic belt. Smaller rivers play an important role in margin sedimentation but are either ephemeral or carry small volumes of water due to the seasonal and sporadic nature of rainfall in most Mediterranean environments. Despite the rainfall regime being highly variable both at the basin scale and regional scale, the precipitation is usually low, often below 500 mm of total annual rainfall. These low precipitation rates, combined with high evaporation and infiltration, explain why most riverbeds are dry most of the year. This makes the closure of the mouths of many Mediterranean rivers by sediment bars a common feature.

The Ebro, Rhône, Po, Danube, and Nile deltas formed after the wedgeshaped accumulation of terrigenous materials at varying sedimentation rates (up to 10 cm/yr). These depositional systems have prograded for hundreds of kilometers since the end of the Messinian salinity crisis, about 5 million years ago. Despite this, the main growth stage defining the deltas we know today started with the attainment of the modern sea-level highstand, from about 8,500 to 6,500 years ago. One of the most studied delta systems in the Mediterranean is the Ebro delta, covering an area of 2,170 km2, of which only ~320 km2 correspond to its subaerial part. The modern delta consists of transgressive and highstand deposits accumulated during the Holocene, from 10,000 years before present to the present. Its shape is inherited both from river influence and marine dynamics. The construction of large dams and the increase in water management along the Ebro system during the last century resulted in the dramatic reduction of sediment discharge at the river mouth. Therefore, the impact of human activities on the shape and development of the Ebro Delta is not only noticeable but will grow in the coming decades.

The Messinian salinity crisis event refers to the drying up of the Mediterranean that produced a dramatic change in the sedimentation and a marked landscape change in the region. In fact, apart from those areas morphologically controlled mainly by deltaic systems or neo-tectonic processes, the present seascape has been strongly determined by the Messinian event. The dramatic sea-level fall (due to the complete closure of the seaways between the Atlantic and the Mediterranean at that time) caused a spectacular change in the rivers' base levels and a major erosional discontinuity in the margin. During this time, a series of evaporites, over 1,500 m thick in some places, were deposited in the Mediterranean basin floors. Salt tectonics related to these deposits are still playing a key role in margin morphodynamics over large areas. Currently, the landscaping impact of the Messinian event can be observed onshore as deeply incised palaeovalleys filled with later sediments. Offshore, it is also thought that the morphology of some deep submarine canyons is inherited from Messinian times.

One of the best examples of continental slope and shelf canyon incision is the Gulf of Lions located in the northwestern Mediterranean (Figure 45). As in other areas of the Mediterranean, some of its canyon systems relate directly to Messinian incisions. Others are linked to the position of former streams during Plio-Quaternary lowstands (i.e., the Last Glacial Maximum lowstand). Other canyons originated through retrogressive slides, independent of former features in the shelf and some are related to faults or salt-tectonics. The shape and dimension of canyons differ substantially from each other. There are canyons deeply incised into the continental shelf, others restricted to the slope, others sinuously shaped, and some with roughly linear morphologies. Mediterranean canyons can be hundreds of kilometers long, several kilometers wide, up to 800 m incised into the slope and with gradients of over 20 degrees on their walls.

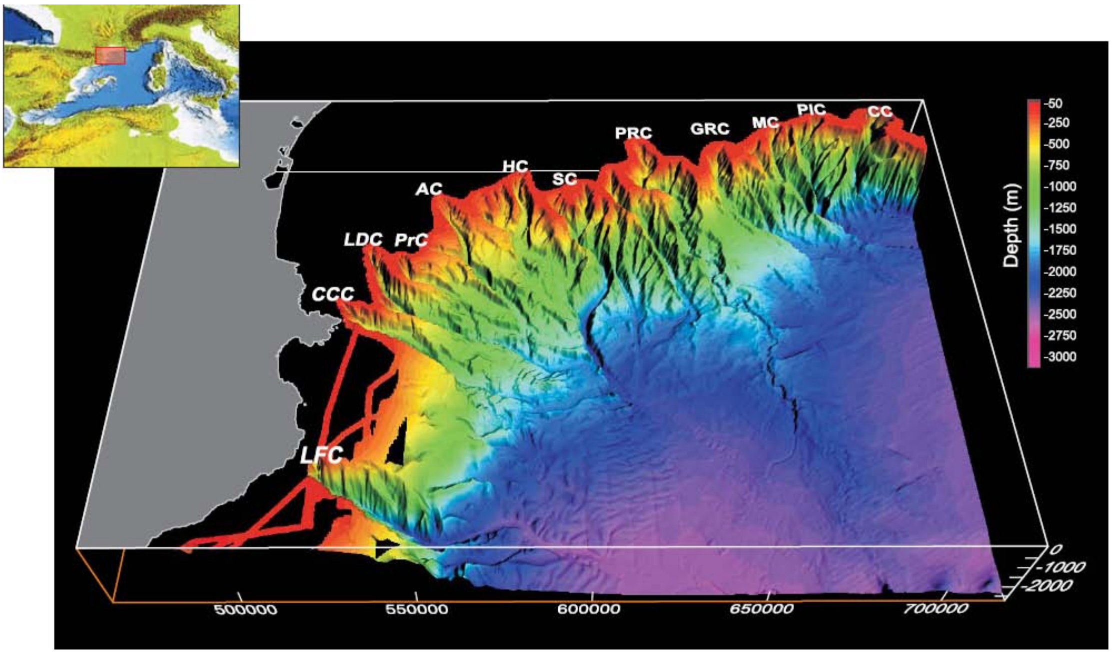


Figure 45 Three-dimensional view of the Gulf of Lions and Northern Catalan margin

Canyons generally evolve downslope to well-developed channel-levee complexes at the base of the continental rise. These sedimentary systems typically supply deep sea fans, which often represent the terminal storage of sediment coming from the surrounding emerged lands. The Nile deep-sea fan, covering about 140,000 km2, is one of the largest submarine fan-shaped terrigenous deposits in the world. Sediments in there are transported by the Nile River drainage system and originate from large eroded areas in the African craton. On the Gulf of Lions' continental rise in the western Mediterranean, large depocenters are also observed. Of these, the Rhône Fan is the largest, with a maximum width of over 90 km.

Slope instability is also a major process mobilizing sediment from the continental slope, even from the shelf edge or further downslope, to the deeper parts of the continental margin. These mass-wasting events can transport huge amounts of sediment and reshape the seafloor very quickly when compared to other previously mentioned processes. In the Mediterranean Sea, numerous mass-movement deposits have been identified. Among these, the BIG'95 submarine landslide is prominent (Figure 46), with a 26 km3 deposit covering 2000 km2 of the Ebro continental slope and base of slope. The occurrence of this event has been dated using sediment cores, giving an age of about 11,500 years before present. Other mass-movement deposits have been identified in the western Mediterranean, mainly on the Gulf of Lions continental rise, where several other quite recent (around 21,000 years before present) debris-flow deposits have been described.

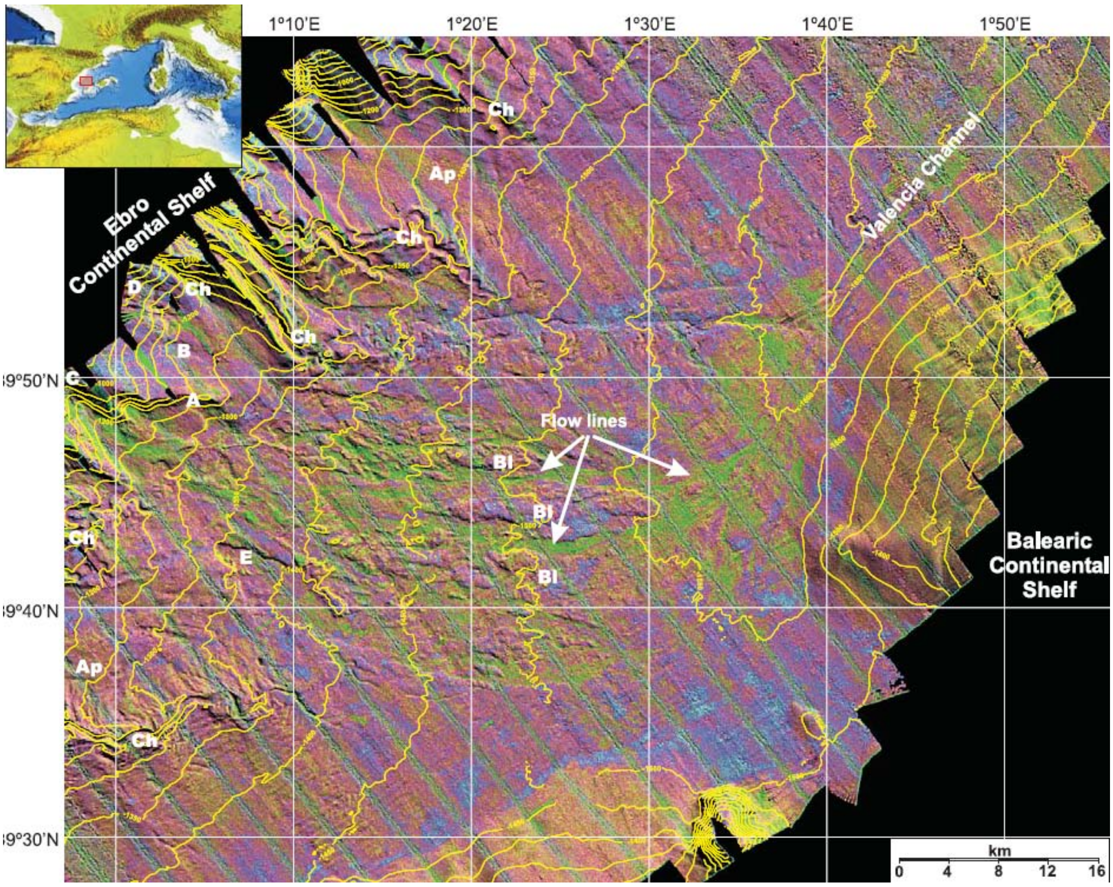


Figure 46 Seafl oor-backscatter data are used to image the product of one of the youngest major mass-wasting events in the Northwest Mediterranean Sea: a 26 km3 debris-fl ow deposit that covers 2,000 km2 of the Ebro continental slope and base-of-slope off shore eastern Iberian Peninsula.

In some cases, submarine canyon channel systems join together at the base of the continental slope or in the continental rise and continue as a single, and often margin-parallel, deep-sea channel. The Valencia Channel, located on the Catalano-Balearic Sea, is a well-developed example in the western Mediterranean (Figure 47). This deep-sea channel trends northeastwards following the Valencia Trough axis, an early Miocene- Pleistocene extensional basin that separates the Iberian margin to the west from the Balearic margin to the east. The Valencia Channel not only collects sediment transported from the canyon channel systems eroded into the Catalan margin, but also from the Ebro turbiditic system and by large unconfi ned mass-wasting events. Among the latter, the BIG'95 submarine landslide, which partially buries the uppermost course of the Valencia Channel, is the most outstanding example. This deep-sea channel fi nally vanishes into the Valencia fan, at the northernmost part of the Algerian-Balearic abyssal plain, 400 km away from its head.

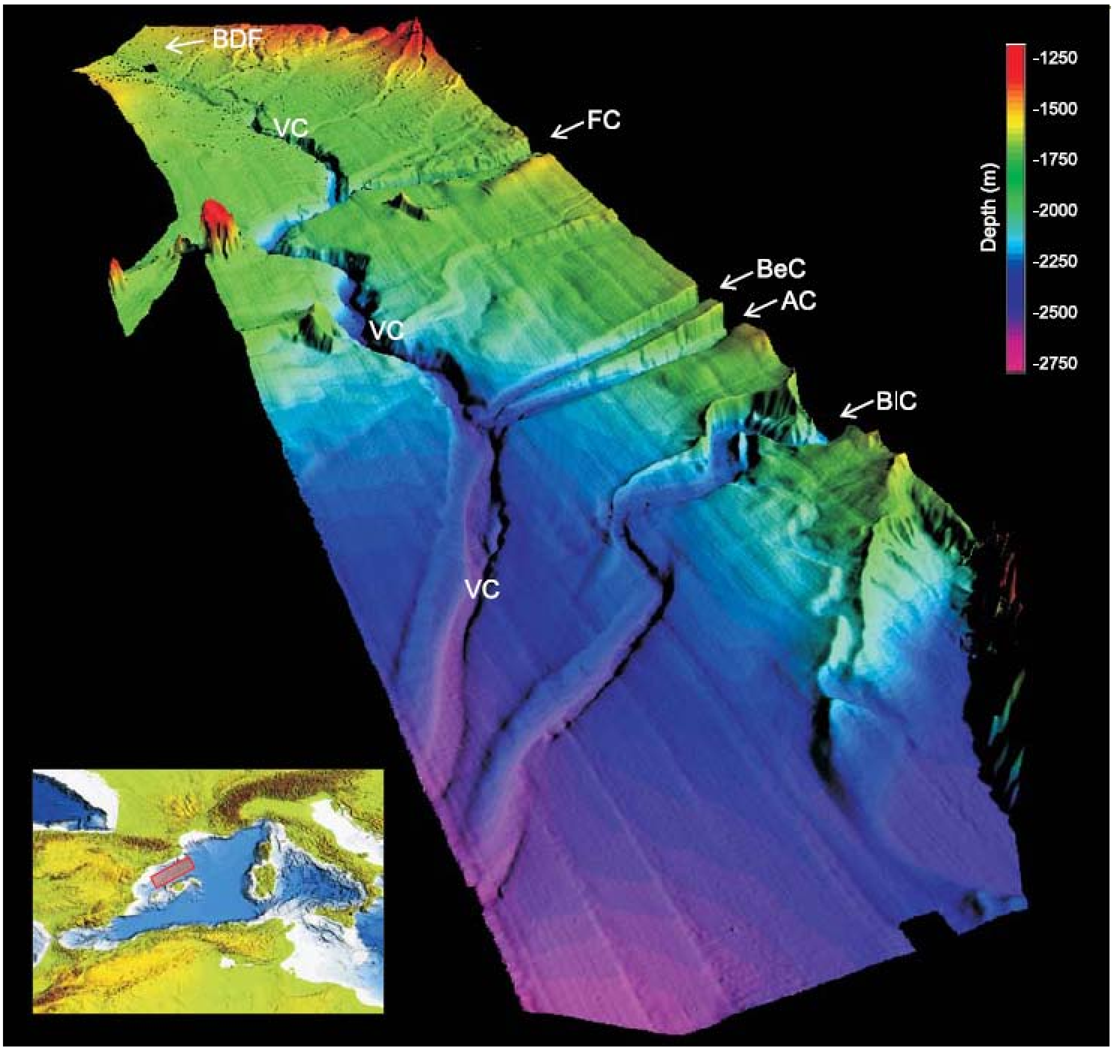


Figure 47 Three-dimensional view of the Valencia Channel

Apart from trenches, the deepest physiographic unit in sea basins is the abyssal plain. In the Mediterranean these are shallower (up to 4,200 m in depth) than those in the larger ocean basins (from 3,000 m to 6,000 m in depth). The sediments in this environment are mainly composed of very fine particles from hemipelagic settling because most of the coarser sediment coming from the emerged lands is left on the continental shelf, slope, and rise. Exceptions occur when large, powerful turbidity currents carry coarse sediment across the abyssal plain from further upslope. In fact, the largest mass-wasting deposit observed in the western Mediterranean Sea is the 60,000 km2, 500 km3 turbiditic deposit that occupies almost the whole Algerian-Balearic abyssal plain. Despite its importance in terms of area and volume, it lacks a prominent signature on the western Mediterranean seascape.

5.6 MEDITERRANEAN CANYON INVENTORY

Several Mediterranean submarine canyons have been investigated from many angles, i.e. circulation, tsunami effects, mass transport, turbidite systems, bottom morphology, biodiversity, cold water biocenoses, fishery impact as well as nursery and recruitment for commercial species, pollution, coast and deep sea exchanges etc. Information on names, numbers, geographical position, morphology, physical and biological processes of the main submarine canyons can thus be now obtained from a broad range of scientific sources covering several Mediterranean areas.

Without exceeding the limits imposed by this review, in this paragraph a very provisional list of canyon names is proposed. The list has been obtained by crossing the above-mentioned datasets with scientific and other sources of information (most can be obtained more or less easily through internet). Canyon names with some reference in literature are in italic style, an asterisk follows the name when it is arbitrarily assigned according to its correspondence with a bay, cape, island, promontory, river, coastal settlement, city or other conspicuous geographical feature. The list also includes canyons still without names, but with some reference to their existence.

South Eastern Iberian Margin

From west to east, the presence of 51 submarine canyons is well documented: *Algeciras*, *La Linea*, *Guadiaro*, *Estepona*, *Bσvedas*, *Baρos*, *Torrenueva*, *Fuengirola*, *Almuρecar*, *Motril*, *Carchuna (Sacratif)*, *Calahonda*, *Dalias*, *Almerνa*, *Andarax*, *Gata*, *Alias Almanzora*, *Palomares*, *Jolocular*, *Aguilas*, *Cabo Tiρoso*, *Cartagena*, *Negrete*, *Palos*, *Alicante*, *Benidorm*, *Valencia*, *Hirta*, *South Columbretes*, *North Columbretes*, *Benicasim*, *Ebro*, *Oropesa*, *Alcalα de Chivert*, *Benicarlσ*, *Marta*, *Peρiscola*, *Torreblanca*, *Tortosa*, *Tarragona*, *Foix*, *Cunit*, *Valldepins*, *Berenguera*, *Morrΰs*, *Besσs*, *Arenys*, *Blanes*, *San Feliu*, *Palamos (La Fonera)*, *Cap Creus.*

Generally, type 2 canyons (incising the shelf without connection with rivers) are located on the eastern and western side, while those confined to the slope (type 3) seem to be mainly from Gata Cape to the mouth of the Ebro.

Balearic Margin

No submarine canyons exist in the north-western slope of the Balearic Islands, while the southern margin is shaped by 4 main canyons: *Pitiusas (Formentera)*, *Mallorca-Cabrera*, *Pera*, *Menorca*. It is also deeply incised by at least 15 short, rectilinear canyons, from Mallorca to Ibiza.

Alboran Island

Three main canyons can be identified on the south and eastern slope off the Alboran Island: Al *Borani, Piedra Escuela* and *Castor*.

French mainland coast

Along the French coast from Cerbere to Menton, 28 canyons can be counted, those of the Gulf of Lion mainly belonging to type 2. From west to east: *Lacaze-Duthiers, Pruvot, Bourcart (Aude), l'Hırault, Sθte, Catherine-Laurence, Marti, Montpellier, Aigues-mortes, Petit Rhτne, Grand Rhτne, Estaque, Marseille, Couronne, Planier, Cassidaigne, Cassis, Siciı, Toulon, Porquerolles, Stoechades, Pampelonne, Saint-Tropez, Estırel, Cannes, Var, Paillon* and *Monaco.*

Corsica

The narrow continental shelf around the Island of Corsica is incised by at least 16 canyons: *Centuri*, Saint-Florent, Ξle-Rousse, Calvi, La Revellata*, Galıria, Porto, Peru*, Sagone, Lava*, Ajaccio, Valinco, des Moines, Porto-Vecchio*, Alıria** and *Cervione*.*

Italian mainland coast

Combining information obtained from various sources, 49 canyons can be identified on the Ligurian, Tyrrhenian and Ionian margin, and two in the southern Adriatic sea. It must be pointed out that in many cases a single name corresponds to a system rather than a single canyon: *Roja, Nervia, Taggia, Verde, Mercula, Bordighera*, Laigueglia, Centa, Varatella, Imperia, S. Bartolomeo, Capo Mele, Pora, Finale, Noli, Vado, Polcevera, Bisagno, Di Levante, Civitavecchia, Gaeta, Garigliano, Volturno, Cuma, Punta Cornacchia, Magnaghi, Dohrn, Salerno, Maratea, Capo Suvero, Angitola, Gioia Tauro, Bovalino, Siderno, Gioiosa, Roccella Ionica, Caulonia, Stilo, Soverato, Catanzaro, Squillace, Corigliano, Neto, Lipuda, Cirς Marina, Taranto, Otranto, Bari*.

Sardinia

A complex system of 29 canyons incises both the western and eastern slopes of the Island of Sardinia: *Caprera, Posada, Gonone, Orosei, Arbatax, Quirra, San Lorenzo, Capoferrato**, *Carbonara, Cagliari, Spartivento* (2 canyons), *Teulada, San Antioco* (2 canyons), *Toro, Carloforte* (4 canyons), at least 4 canyons off the southwestern coast (Costa Verde), *Oristano, Il Catalano*, and at least 3 canyons off the coast from Bosa to Capo Caccia, *Castelsardo*.

Sicily

Around Sicily, 21 canyons are mainly located off the northern and eastern coasts: *Egadi, Stromboli, Patti, Messina, Milazzo, Castellammare, S. Vito, Cofano, Zafferano, Eleuterio, Oreto, Arenella, Priola, Addaura, Mondello, Favignana, Pantelleria- Mazara**, *Scoglitti**, *Capo Passero* and *Catania*, which indicate

canyon systems.

Malta

Heron is the canyon name located off the south-eastern side of the shelf around the Maltese archipelago. This canyon is divided into two branches in its deepest portion.

Tunisia

The long *Bizerte* canyon cuts the channel northward between Sardinia and Tunisia, while its eastward branch reaches Rass Sidi el Mekki (Cape Farina). Another 3 canyons carve the shelf around the Galite Island.

Algeria

The Algerian steep slope is shaped by 24 canyons. References to *Annaba, Skikda, El Kebir, Nil, Bejaoa, Dellys, Sebaou, Nif, Sefsaf, Algiers, Dahra, Guelta*, and *Khadra* canyons can be found in both scientific literature and the Google Earth digital atlas. Between Algiers and Dahara, at least 11 unnamed canyons can be identified.

Morocco

The southern portion of the Alboran sea is mainly characterized by submarine hills and banks: the only submarine canyon is close to *Ceuta.*

Greece

The Hellenic Trench, stretching from the Ionian Islands to Rhodes (southern Aegean arc), is characterized by numerous canyons, as is the northern part of the Aegean sea: *Kerkyra, Paxoi**, *Lefkas, Kefalonia, Zakynthos, Pirgos*, Kiparissiakos*, Proti*, Messini*, Kalamai*, Kyparissia*, Kalamata*, Skoutari*, Mirampelou** (Crete), *Samaria* (Crete), *Paximades*, *Sfakia** (Crete), *Ptolemy* (Crete), *Lithinon* (Crete), *Pliny* (Crete), *Strabo* (Crete), *Nereus* (NW Rhodes), *Brigitte* (NW Rhodes), *Trianta* (NW Rhodes), *Kallithea**(NE Rhodes, 2 canyons), *Psalidos* (NE Rhodes), *Pera* (NE Rhodes), *Lutani** (NE Rhodes), *Tsampika** (NE Rhodes, 2 canyons), *Malσna**(NE Rhodes), *Vlichα**(NE Rhodes), *Lindos** (NE Rhodes), *Samotrδki** (2 canyons), *Strymonik**, *Thermaikos* (2 canyons). Very likely the number of canyons in this area is underestimated.

Turkey

At least 11 main submarine canyons can be identified off the western and southern Turkish coasts, as for Greece, their number may be greatly underestimated: *Xeros**, *Bosphorus, Sarkφy, Anadolu, Fethiye, Megisti**, *Finike, Antalya, Anamur, Boziaz*i*, *Antakya**.

Cyprus

Around Cyprus 5 canyons have been identified: *Famagusta*, Larnaka*, Akrotiri*, Chrysochou** and *Morphou*.*

Middle East coast

Latakya, Baniyas, Tartus and *Sour* are the names identifying submarine canyons off the Syrian coast and *Junieth, Saint Georges, Beirut, Zahrani, Sayniq* off the Lebanese coast. *Akhziv, Saar, Nahariya, Shomrat, Hilazon, Qishon, Haifa, Atlit, Cesarea, Hadera, Netanya, Ashdod* and *Afiq* are the names of the canyons off the coast of Israel which are mainly cited in geological literature.

Egypt

The Egyptian passive margin is incised by 12 canyons: *Damietta** (a system with at least 7 branches), *Rosetta* (a system with at least 9 branches), *Alexandria**, *Ras Alam er Rum*, *Solum** and *Habu Ashafa**. At least 6 canyons from Solum to Habu Ashafa still remain unnamed.

Lybia

Canyon density is higher off the eastern coast: many of them have been named arbitrarily or are still unnamed: *Tobruk**, *Derna** and at least five canyons in between, one canyon west of Derna. *Susah** and another four canyons to the west before *Melita*, *Misratah* and *Tripolitanian.*

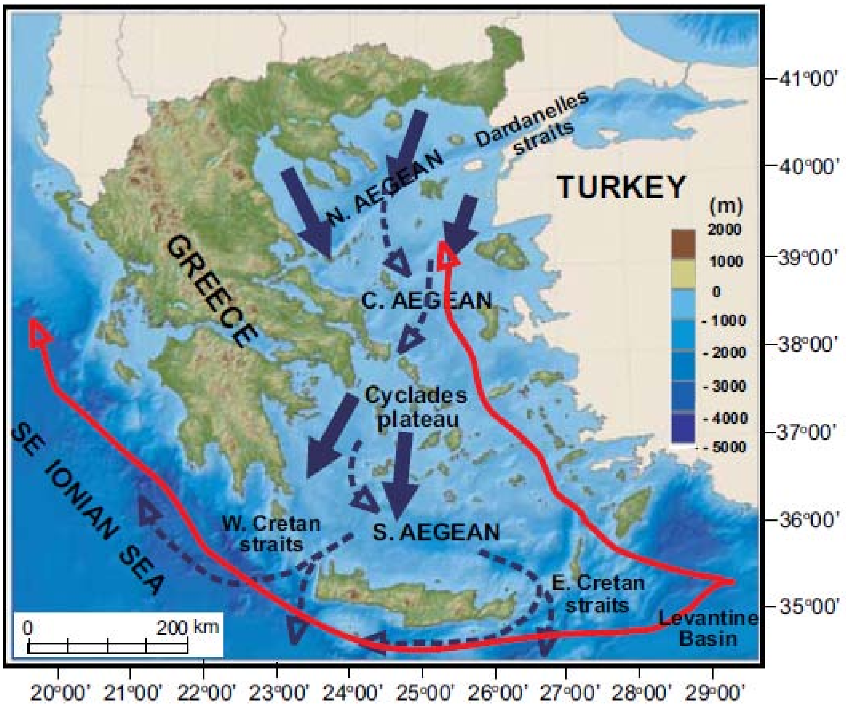
Roughly, a total of 348 submarine canyons or canyon systems can be allocated on the slopes of the eastern and western Mediterranean basins, and 237 have a name quoted in scientific literature or other sources of information. The geographic position of the remaining 111 can be identified, but it has not been possible to find references in order to assign a shared name: nevertheless 47 of them have here been arbitrarily attributed a nomenclature. Comparing these figures with the results obtained by Harris and Whiteway (2011), this list greatly underestimates the number of Mediterranean submarine canyons, mainly for the southern Tyrrhenian coast of Italy, Algeria, the south Aegean Arc and Turkey. It must be stressed that this very provisional inventory is roughly based on the available information obtained from scientific literature and other kinds of sources; it does not fit specific criteria in order to identify various types of canyons and, sometimes, canyon systems from a single canyon. Even if available in some cases, data such as the geographic position (i.e. head and mouth coordinates), length, shape (V or U shaped), type (i.e. shelf incising, shelf incising with river connection, slope confined), habitat type (i.e. sandy, muddy, rocky), biocenoses (i.e. cold water corals), role for fisheries (i.e. nursery, breeding, ground), threats, exploitation for non-renewable resources, pollution, conservation status etc. have not been considered at the moment. Obviously, a Mediterranean submarine canyon inventory exceeds the objectives of this review: nevertheless, considering the fundamental role of such structures for shelf and open sea exchanges, it could be a priority tool for better governance of the entire Mediterranean ecosystem.

CHAPTER 6

THE AEGEAN SEA

6.1 The Aegean Sea

Due to a complex, long-term geodynamic evolution and active neotectonics, the Aegean Sea displays a complicated physiography in terms of seabed morphology and land-sea configuration. The seafloor topography of the North Aegean is characterized by a series of deep trenches and troughs with depths reaching 1500 m, separated by shallow sills and shelves. An extended shallow sill, the Cyclades plateau, which is shallower than 200 m, separates the Central from the South Aegean Sea (Figure 48). The combination of the influx from North Aegean rivers and the inflow of low-salinity Black Sea Water (BSW) through the Dardanelles, together with air-sea interactions, creates an intricate hydrological system that acts on water-mass hydrology, circulation, and biological, chemical, and sedimentological processes in the Aegean Sea. The variability of the system, most pronounced along north-south trends, and the spatial variability of trophic conditions create a unique area for the study of biogeochemical fluxes.



Fiure 48 Three-dimensional view of the Aegean Sea

Water circulation in the Aegean Sea follows, in general, a cyclonic pattern. However, the most active dynamic features of the Aegean are the mesoscale cyclonic and anticyclonic eddies. The inflow of BSW is the major source of brackish water for the North Aegean; the contribution of all the rivers discharging into the Aegean is less than the input of BSW by at least one order of magnitude. The flux of the BSW in the North Aegean varies from 100–1000 km3 yr-1.

The South Aegean Sea, also known as the Cretan Sea, is the largest in volume and the deepest Aegean basin, reaching 2500-m depth. The Cretan Sea is connected to the Levantine basin and the Ionian Sea via the eastern and western Cretan straits through sills varying in depth from 150–1100 m. The hydrology and water mass dynamics of the South Aegean Sea are known from historical work and recently from analysis of data gathered within the framework of national, international, and European programs. These investigations revealed the intense mesoscale variability that characterizes the circulation pattern in the South Aegean Sea and the Cretan straits. A succession of transient and/ or recurrent cyclonic and anticyclonic eddies defines the water-mass distribution. Winter convection processes lead to intermediate and/or deep water-mass formation.

In the mid and late 1980s, the upper layer in the South Aegean was occupied by either (1) surface saline ($S \sim 39$) waters of Levantine origin (LSW), occurring during the warm period of the year within the upper 50 dbar layer, that enter the Southeast Aegean through the eastern Cretan straits, or (2) the lesssaline ($S < 38.9$) surface BSW coming from the North Aegean and affecting mainly the Mirtoan and western Cretan seas. Moreover, most of the time there were intrusions through the Cretan straits of less-saline subsurface water of Atlantic origin, the so-called Modified Atlantic Water (MAW), coming from the Ionian Sea. Below the upper layer and down to the bottom, two denser (σt up to 29.16) water masses were distinguished: the LIW and the Deep Cretan water that contributes to the layers below the LIW in the eastern Mediterranean basin.

In the early 1990s, the structure of the deep Cretan Sea water column changed dramatically, as exceptionally dense ($\sigma t > 29.2$), very saline ($S > 39$) water of local origin started filling the deep Cretan basin and overflowed through the sills of the Cretan Arc straits. Due to its high density, Cretan Deep Water displaced water from the deepest parts of the Levantine and Ionian basins in the eastern Mediterranean. Thus, the Aegean became the major contributor of warmer and more saline bottom water to the eastern Mediterranean.

Immediately after cooling, the newly formed dense surface water sinks rapidly and flows southward directly above the seabed, thus flooding the deeper part of the Cretan basin. After filling the Cretan basin, the dense water overflows the Cretan straits and cascades through the canyons of the southwest flanks of the straits and spreads into the deep eastern Mediterranean, flooding the deep Ionian basin.

Side-scan sonar and 3.5-kHz profiler images showing numerous sandy bed forms on the north-northeast Cyclades plateau indicate the flow and cascading of dense water. The bed forms occur in depths of 80–130 m as: (a) dunes (wave length 10–35 m and height 1–2 m) composed of moderately well-sorted coarse sand, (b) large to very large sand waves (wavelength 50–300 m and height 1.5–6 m) usually developed in fine to medium sand, (c) megaripples (wavelength 3–5 m and height

0.2–0.4 m), (d) narrow sand ribbons, and (e) elongate sand patches. Shortperiod deployments of near-bed current meters recorded maximum values up to 10–15 cm s-1 with mean velocities of 6–7 cm s-1 and therefore failed to record the peak flow required to generate these bed forms. Such bed forms imply a strong, near-bed episodic southern flow on the order of 40–100 cm s-1 and, locally in the case of sand ribbons, up to 200 cm s-1. Dense (deep) water that forms in the North and Central Aegean (including the Cyclades plateau) during exceptionally cold and dry winters subsequently sinks and flows over the seabed, causing these forms to develop.

The South Aegean clearly reflects the very oligotrophic character of the Aegean Sea. Downward matter fluxes are higher in the North relative to the South Aegean. Substantially higher values of near-bottom mass fluxes were measured in the deep basins of the North Aegean, implying significant deep lateral (advective) fluxes of particulate organic matter (POM). The North Aegean could be classified as "continental margin" ecosystem, while the South Aegean is a typical "oceanic margin" oligotrophic environment.

As a consequence, the Cretan Deep Water overflowing the Cretan straits and cascading toward the Ionian basin transports insignificant amounts of POM and nutrients but is rich in oxygen. However, episodic down-canyon POM fluxes have been observed by means of sediment traps deployed in the canyons of the Cretan straits.

In one study was used an intercalibrated set of eastern Mediterranean oxygen data collected from 1987 to 1999 to study the evolution of oxygen concentrations that accompanied the early 1990s changes in thermohaline circulation (dense deep water) of the eastern Mediterranean. They found that by the late 1990s the deep layers had considerably elevated oxygen concentrations compared to 1987 because of the cascade of oxygen-rich near surface waters into the deep layers during 1990–1995. These authors also proposed that this massive invasion of near-surface waters supplied large amounts of dissolved organic carbon with an unusually high fraction of labile material, which in turn enhanced oxygen consumption. Dissolved organic carbon and mesozooplankton ecology data provide supporting evidence. The enhanced oxygen consumption represents a further example of disturbance in the biogeochemistry of the eastern Mediterranean related to dense water cascading.

6.2 The submarine canyons of the Rhodes basin and the Mediterranean coast of Turkey

6.2.1 Introduction

The Levantine Basin is one of the three main deep basins of the Mediterranean Sea and exhibits particular geological structures such as depressions, cold seeps, shallow and deep sea marine canyons, seamounts and mud volcanoes. The eastern

Mediterranean coastal zone contains very special geomorphological features due to coastal evolution and rock type.

The morphology of the East Mediterranean seafloor is the consequence of both early formation processes of the deep basins and recent geodynamic microplate interactions. Thus, the East Mediterranean Sea constitutes the last remnant of the Mesozoic- Cenozoic oceanic basin of Tethys, now almost totally consumed by the long-term Eurasian and African plate convergence.

The arc-shaped East Mediterranean Ridge (EMR) characterizes the subregion from the south-west Peloponnesus to southern Crete and Rhodes. The EMR is 1,500 km long and 200–250 km wide and it is the result of relatively rapid Eurasian and African convergence and the subsequent subduction of the oceanic crust beneath the over-riding Aegean microplate and the deformation of its sedimentary cover. The deep trenches north of the EMR, such as the Strabo and Pliny trenches to the east, form the Hellenic Arc, which is the morphological expression of geological processes in the fault-zones. Numerous canyons and deep valleys originate from the shelf off the mainland and main islands, ending in the trenches and bordering basins. Of particular interest is the seafloor topography of the East Cretan Sea and Levantine basin, which are characterized by complex morphology with narrow canyons running between steep sloped ridges. The Hellenic Arc terminates eastward in the Rhodes basin, a relatively young basin, 4,000- 4,500m deep, east of the Island of Rhodes, characterized by the cyclonic Rhodes gyre driving constant upwelling, which affects the entire productivity of the Levantine sea.

6.2.2 The Rhodes Gyre

The Rhodes Gyre (Fig. 49) rotates anti-clockwise forming a distinct vertical cylinder of eastern Mediterranean water to the south of the island of Rhodes. It is likely that this cyclonic gyre results from winddriven basin circulation, and the interaction of the main currents with land masses and seafloor morphology (i.e. Rhodes Trench). This cyclonic rotation causes deep water, rich in nutrients, to rise from the bottom to the surface and in consequence the Gyre is much more fertile than the rest of the eastern Mediterranean, which is known as one of the most oligotrophic (nutrient-poor) aquatic environments in the world because of its extremely low primary production.

Napolitano *et al.* (2000) have studied the biological production characteristics of the Rhodes Gyre through a one-dimensional, coupled physical–biological model using single aggregated compartments of phytoplankton, zooplankton, detritus, as well as ammonium and nitrate forms of inorganic nitrogen. It interacts with the physical model through vertical eddy diffusivity. The model simulations demonstrate the importance of physical oceanographic characteristics affecting yearly planktonic structures, and shows that annual primary production in the Rhodes basin is comparable with the north-western Mediterranean. The Rhodes basin reveals a strong bloom in early spring, typically in March, a weaker bloom in early winter, typically in January, and a subsurface production below the seasonal thermocline during the summer.

The strong and permanent effect of the Rhodes Gyre on offshore primary production in the Rhodes basin is also linked to the area's particular geomorphology, which is characterized by a deep trough bordering Rhodes Island to the west, Finike seamounts (Anaximander) to the east and Finike basin to the south-east, and by the effect of the in-flow of water masses trough the Karpathos Straits as well as the presence of several submarine canyons.

Even if the processes of deep-water fertilization in this area are poorly investigated up to now, submarine canyons may have a role by enhancing the flux of nutrients from the land, as in other Mediterranean areas. Moreover, recent evidence has indicated that the current oligotrophic nature of the eastern Mediterranean may shift to a more productive system due to increased anthropogenic influences and consequent global changes (changes in nutrient flux, CO_2, temperature). These changes may fundamentally affect the biological components of the system from primary production through all levels of the food-web.

Finally, the cyclonic Rhodes Gyre is confined by three anticyclonic gyres; Ierapetra to the south-west, Mersa-Matruh to the south and the West Cyprus Gyre to the east, thus forming a large oceanic triad system which enhances reproductive habitat suitability for small pelagic species thanks to co-occurring mechanisms: nutrient enrichment, concentration of larval food distributions, and local retention of eggs and larvae.

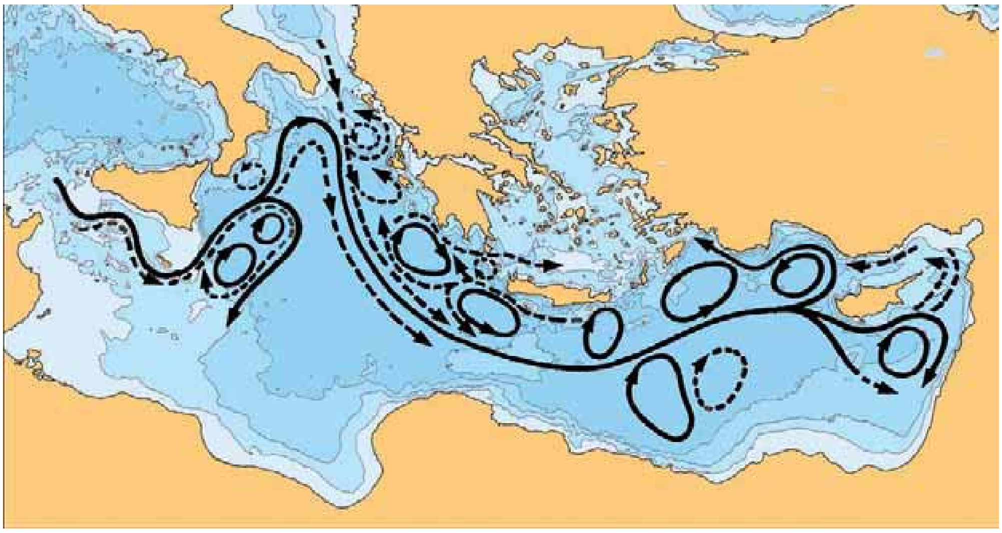


Figure 49 Rhodes Gyre and other key oceanographic structures in the east Mediterranean Sea

6.2.2 Effect of south-western Anatolia submarine canyons on biodiversity

A very narrow shelf characterizes the south-western Anatolian coast and several canyons connect the abyssal floor of the Rhodes and Finike basins with the upper shelf. Notably, these canyons and submarine landslides are active channels which have been interpreted as having been triggered by on-going faulting and which attest to substantial present-day direct clastic sedimentation from Turkey and the Island of Rhodes into the above-mentioned basins.

In the deepest part of the Levantine basin, the noticeable correlation of benthic production with distance from land masses confirms that the lateral transport of organic matter through submarine canyons plays a major role. Moreover, the patchiness of macrofauna abundance indicates that the deep Levantine Sea is an eventdriven system, in which terrestrial run-off affects the functioning of the community by spatial variability in food ingression events.

The south-western Anatolian continental slope delineates the north-eastern margin of the Rhodes Basin; here the slope face is dissected by numerous submarine canyons.

Around the Island of Rhodes, the continental shelf on the western side appears to be generally smooth, while on the eastern side it is steeper and cut by a number of submarine canyons; here, depths of over 350 meters are encountered less than one mile seaward of the 200-meter contour.

Most of the submarine canyons are located on the north-eastern platform portion where the continental slope is inclined from 8° to 15°. A major canyon, Nereus canyon, extends to the north-east from the northern tip of the island, and two more canyons, Brigitte and Trianta, as well as several small V-shaped sea valleys, are located in Trianta Bay on the north-western side of the Island.

Goedicke (1977) identified at least ten main submarine canyons between Rhodes and Lindos, and a number of slope gullies, which seem to be associated with the on-shore topography. Within Kallithea Bay, two canyons incise the shelf; in Afantou Bay, two canyons exist in association with the mouths of the Psalidos and Pera rivers; offshore from Tsampika, the head of the major canyon was likely to have been connected with the ancient Lutani river-mouth, which was in the past to the south of Cape Vahyah, and has now shifted to its northern side; between Tsampika and Cape Archangelos, two smaller canyon heads lie near the mouth of two intermittent rivers; in Malona Bay and Vlicha Bay, another two canyons and one main canyon offshore from Lindos (Cape Sumani and Cape Foca) have no connection with presentday river valleys. All these factors lead to the conclusion that the northernmost canyon off the east side of Rhodes Island originated due to subaerial erosion, while the southern ones are of tectonic origin, being located close to a very active fault. At the present time, the canyon axes are probably the result of erosion due to submarine slumping, triggered by large, long-period waves during south-easterly winter storms.

The Rhodes basin can, in fact, be divided into two sub-basins: a deeper northern one, and a shallower southern one, separated by a broad, asymmetrical swell oriented east–west. The northern margin of the basin is interrupted by the large, north-east oriented Fethiye canyon, which extends into the Turkish shelf and Fethiye bay. Along the Fethiye canyon an important fault zone occurs, forming the north-eastern extension of the Pliny Trench, while the southern sub-basin lies in morphological continuity of the Strabo Trench.

In general, the Mediterranean Turkish shelf and slope appear to be significantly dissected and transected by canyons and gullies. Even if many of these canyons can be classified as blind canyons (confined to the slope), some of them are the extension of canyons on land, such as Saklikent canyon, or correspond with river mouths (i.e. Dalaman and Esen Streams) (Fig. 50).

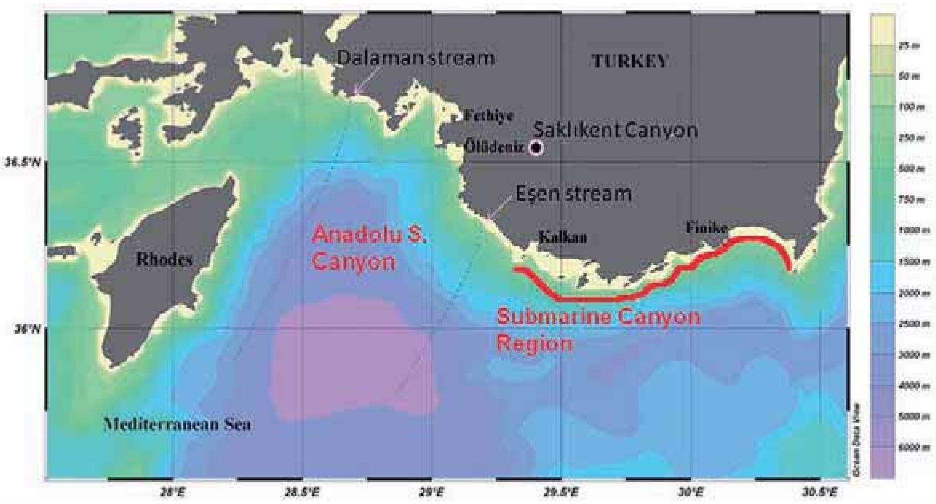


Figure 50 Submarine canyon region in the Turkish part of the Mediterranean Sea.

Between Kalkan and Finike, a number of shallow coastal canyons incise the upper shelf becoming deeper even very close to the shore: they play a role of stepping stones between the coast and the open sea (Fig. 51). Spawners and recruits of many fish species, which migrate from the Beymelek and Koycegiz lagoon system to off-shore habitats and vice-versa, use these coastal canyons. Coastal canyon communities generally consist of sponges *(Axinella verrucosa, A. polypoides*), some lobster species *(Scyllarus arctus* and *S. latus)*, as well as stony corals such as *Caryophilia* spp.

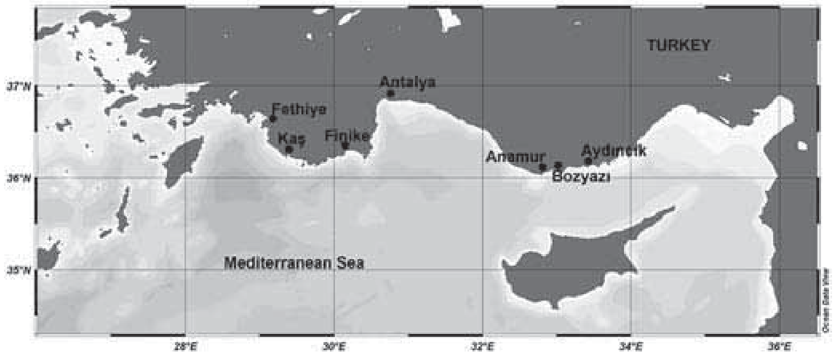


Figure 51 Map of coastal canyons in the Turkish part of the Mediterranean Sea.

Evidence of macrofaunal abundance and the diverse conditions of marine invertebrates in the Eastern Mediterranean have been discussed by Danovaro *et a*l. (2010). Megabenthic species have been reported at depths between 400 m and 4,264 m, including 20 species of decapod crustaceans such as the endemic geryonid crab (*Chaceon mediterraneus*); one species, *Levantocaris hornun gae*, was described as new to science and *Polycheles typhlops*, *Acanthephyra eximia*, *Aristeus antennatus*, *Calocaris macaendreae*, *Parapenaeus longirostris* and *Geryon longipes* were found to be dominant in the Cretan Sea and Rhodes basin; *Scopelocheirus hopei*, *Scopelocheirus polymedus*, *Orchmenella nana*, *Orchomene grimaldi*, *Epimeria* cf. *cornigera* were the most abundant amphipod species recorded by baited trap, and *Ileraustroe ilergetes*, *Pseudotiron bouvieri*, *Rhachotropis rostrata* and *Stegophaloides christianiensis* are amphipod species endemic to the Mediterranean; among cumaceans, *Procampylaspis bonnieri*, *Campylaspis glabra*, *Makrokylindrus longipes*, *Platysympus typicus* and *Procampylaspis armata* were the most frequently collected, while *Yoldia micrometrica*, *Kelliella abyssicola*, *Cardyomia costellata*, *Entalina tetragona*, *Benthomangelia macra*, *Benthonella tenella* and *Bathyarca pectunculoides* were the most common benthic molluscs identified at depths greater than 1,000 m.

The Anatolia canyon (i.e. Fethiye canyon) extends down to the deep depression of the Island of Rhodes between Turkey and Greece, hosting deep-sea fish species including *Bathypterois dubius*, *Nezumia sclerorhynchus*, *Cataetyx laticeps*, *Chauliodus sloani*, *Coriphaenoides mediterraneus*, *Nettastoma melanurum* and *Lepidion lepidion* were the most abundant species. In the Rhodes Basin and at depths less than 2,300 m, the most abundant shark species were *Hexanchus griseus*, *Galeus melastomus*, *Centrophorus granulosus*, *Centroscymnus coelolepis*, and *Etmopterus spinax*.

In recent studies, twenty-three fish species were collected or photographed in the Levant Sea at depths greater than in the Western Mediterranean, some nearly doubling the depth record of the species.

Larger-scale upwelling and downwelling structures of cyclones and anticyclones, dominating circulation in the central area of the Rhodes basin and Anaximenes Mountain (Fig. 52), affect the zooplankton community. Zooplankton standing stocks, at a generally low level due to the oligotrophic character of the eastern Mediterranean, were found to be higher in the Rhodes Basin than on the seamount, probably also influencing the distribution of top pelagic pradators.

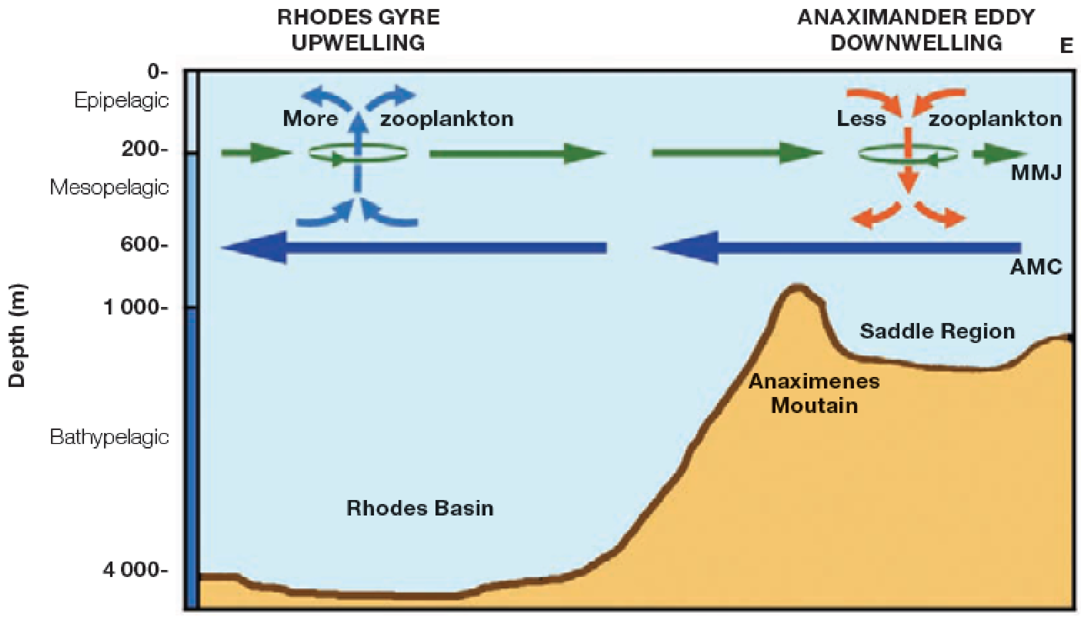


Figure 52 Conceptual model of water mass circulation effect on zooplankton in the Rhodes Basin and Anaximenes Mountain region

Cetaceans have also been observed around the Anatolian canyons. Mostly *Stenella coeruleoalba*, *Delphinus delphis*, *Ziphius cavirostris* and *Grampus griseus* have been reported. The sperm whale is strictly teuthophagus and 14 cephalopod species were found between Rhodes and Fethiye deep zone. This deep-sea upwelling canyon zone provides feeding grounds for whales and dolphins, mostly for sperm whales (Fig. 53). In 2010, 34 sperm whale sightings were reported in the upwelling canyon zone between Rhodes and Fethiye. Moreover, the submarine canyons from Finike to the south-eastern Anatolia region are spawning grounds for several migratory fish species, such as scombrids and bluefin tuna (*Thunnus thynnus*). Beaches in this area are nestling grounds for sea turtles, *Chelonia mydas* and *Caretta caretta* have also been observed offshore between Rhodes-Finike and were most probably feeding.

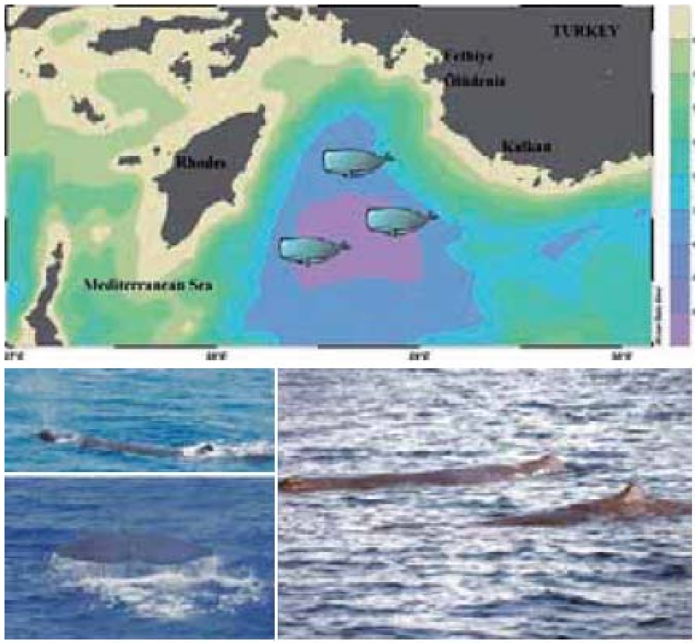


Figure 53 Sperm whale feeding zone in upwelling canyon zone.

CHAPTER 7

ECOSYSTEM AND FINANCIAL IMPACT

7.1 The ecological role of canyons

The interplay between canyon topography and oceanic currents has profound consequences for the diversity, functioning, and dynamics of both pelagic and benthic communities. For example, currents funneled through canyons likely enhance primary productivity and drive sediment transport and associated particle-reactive substances toward deep environments. Higher levels of primary productivity may lead to canyons being hotspots of faunal productivity in the deep sea. The highly variable seascapes within a canyon support diverse assemblages of species that play a wide variety of ecological roles, often across small spatial scales, giving rise to enhanced biodiversity, and ecosystem function. Given their local importance, canyons represent a relevant regional source of marine biodiversity and ecosystem function.

7.1.1 Canyon Effects on Local Circulation and Sedimentation

On many continental margins, cross-shelf exchanges of water, and particulate matter are inhibited by the presence of density fronts and associated slope currents flowing parallel to the isobaths. Submarine canyons intercept the path of these currents, inducing a new dynamic balance, eventually enhancing non-geostrophic motions, and shelf-slope exchanges. Near the seafloor, alignment of the current with the direction of the canyon axis is commonly observed. The adjustments of the current to the canyon topography produce vortex stretching and vertical motions. These modifications of the currents may result in local upwelling, which pumps nutrients to the euphotic zone and thus stimulates primary production. Additionally, closed-circulation cells and downwelling may develop over canyons, enhancing the capacity of the canyon to trap particles transported by long-shore currents. When thermohaline stratification of the water column is strong, the flow in the upper mixed layer may decouple from the underlying water levels, which interact with the rims of the canyon. In such a scenario, the current flowing above the canyon head tends to follow its path, ignoring the bottom topography, while the flow below the rim is deflected by the canyon. This current flow can also induce the formation and focusing of internal waves.

Most of the particulate organic matter introduced into the marine environment by riverine inputs and coastal surface productivity, particularly the most labile fraction, is mineralized after several cycles of seafloor deposition/resuspension on the continental shelf. In contrast to this scenario, canyons act as morphological shortcuts, accelerating the transit of particles from fertile coastal and inner shelf environments toward the deep sea, thus enhancing the role of canyons as sedimentary depocentres, where enhanced oxidation and burial of organic carbon occurs. Additionally, large storm waves, hyperpycnal flows, dense shelf- water cascades, earthquakes, and other processes trigger mass failures of unstable deposits within canyon heads and on the shelf-edge areas of shelf-incising canyons. Sediments (and associated organicmatter) entrained in turbidity flows are exported from the canyon system for deposition on adjacent submarine fans. Thus, particle fluxes and sediment accumulation rates have been found to be much larger inside submarine canyons than in the adjacent non-dissected margin at comparable depths.

7.1.2 Canyon Effects on Pelagic and Motile Benthic or Demersal Fauna

In the pelagic realm, the diversity, and complexity of food webs increase in response to canyon-induced upwelling of nutrients. The high level of primary production attracts pelagic- associated secondary and tertiary consumers. Abundances of mega faunal species, including a variety of demersal fishes, large pelagic predators such as tuna, swordfish, and sharks, as well as cetaceans and birds, are enhanced. All these predators are likely to be present in canyon areas for feeding and breeding, albeit intermittently in some cases. For example, demersal fishes, such as macrourids and cusk (*Brosmebrosme*), in Baltimore and Norfolk canyons (NW Atlantic) , prey upon larges warms of euphausiids and amphipods as well as benthic species ,such as brittlestars, which are abundant because of canyon-enhanced productivity. In addition, canyons may concentrate motile megafauna that leave the adjacent slope in an attempt to evade visual predators by hiding within the complex canyon topography recorded high numbers of sablefish (*Anoplopoma fimbria*) along Barkley canyon walls at approximately 900m depth from the NEPTUNE Ocean Observatory, Canada. Canyon geomorphology can trap dielvertical migrants, such as hyperiid amphipods and euphausiids, when wind-generated currents push animals toward the canyon heads. These trapped individuals regain their original depth position by swimming along the seabed, adopting a more nektobenthic mode of movement, in order to restart a new vertical migration cycle.

The accumulation of organic matter, caused by the physical and geological characteristics of some submarine canyons, promotes higher abundances, biomass, and diversity of organisms compared to the adjacent open slope. These conditions have been observed at eutrophic canyons along continental margins as well as in those associated with oligotrophic conditions on oceanic islands. Elevated sedimentation rates inside submarine canyons can favor benthic detritivores and fauna capable of rapidly conveying the organic material produced in the upper water column, thereby processing large amounts of carbon for input into the benthic food web. Canyons can also influence the depth distribution and population structure of particular species during the various stages of its lifecycle, thus affecting the distribution of biomass and density of specific lifestages. Forexample, in some fishes (e.g., monkfish *Lophiuspiscatorius*, hake *Merlucciusmerluccius*), larger spawning females have been more commonly observed inside submarine canyons (e.g.,Petit-RhôneandGrand-Rhône) than on the adjacent opens lope. Additionally, canyons can act as recruitment grounds for some species of fishes and crustaceans. High abundances of egg cases of an unknown species of scyliorhinid catshark were found among coral in Mississippi Canyon, Gulf of Mexico. In the Gulf of Lions (NW Mediterranean), periodic dense shelf-water cascading events supply large amounts of organic material to bathyal and abyssal areas. Recruitment of the highly mobile deep-sea shrimp *Aristeusantennatus* is enhanced in years following such events. In Blanes Canyon (NW Mediterranean), benthic, and intermediate nepheloid layers, with significant amounts of suspended sediment, are present year round. There is evidence that the juveniles of some deep-sea shrimps (*Plesionika heterocarpus*, *P.edwardsi*, *P.giglioli*, *and P.martia*) and fishes (*Phycisblennoides*, *Moramoro*, *Lepidionlepidion* amongst others) concentrate in the benthic intermediate nepheloid layers this canyon, which act as a nursery area for these species.

7.1.3 Canyon Effects on Benthic Sessile Fauna and Infauna

In the benthic realm, enhanced primary production and current regimes provide suitable ecological niches for large and abundant suspension and filter feeders, such as sponges and cold-water corals (Figure 54). Resuspension of particulate organic matter (POM), combined with as lower deposition of particulate matter descending from the euphotic zone, leads to higher levels of particulates and nutrients in the water column inside canyons, resulting in enhanced primary productivity. Suspension feeders and demersal planktivores likely benefit from these high concentrations of primary producers. In Whittard Canyon (Celtic Margin of the NE Atlantic), accelerated currents increase the organic matter influx and therefore the availability of food compared to less active areas on the continental slope. In the upper region of Whittard Canyon (700m depth), a very dense assemblage of corals and large bivalves was observed associated with an epheloid layer that might provide a significant amount of food. Furthermore, the scleractinian coral *Lophelia pertusa* was observed at great depth and higher densities in this canyon, than usually recorded in the NE Atlantic. The deepening of the distribution of *L.pertusa* could be related to down slope transport processes in canyons. Likely mechanisms for food transport include hydrodynamic processes such as gravity currents and internal waves, or by the trapping effect of the canyon topography itself. Similarly, high densities of gorgonians, pennatulids, and sponges in Pribilof and Zhemchug canyons (Bering Sea) may be supported by enhanced levels of primary productivity delivered by strong currents. Likewise, canyons intersecting the shelf break in East Antarctica, experience strong currents and particle fluxes and support dense communities of corals and sponges.

Patches of detritus have been described as hot spots of food resources in canyons. These patches not only support locally high numbers of deposit feeders that benefit from the accumulation of macrophyte detritus, but also a variety of crustaceans associated with down-welling. Overall, the presence of detritus patches in canyons provides an additional food source, contributing to higher densities, and biomass of infauna in canyon sediments than in sediments on the adjacent shelf and slope. Is examined meiofaunal assemblages in five submarine canyons and adjacent slope habitats along Portuguese, Catalan, and Adriatic margins. Their results suggest that available food sources, including detritus, as well as topographic and hydrodynamic features of canyons, influence meiofaunal abundance and biomass.

Within canyons, the complex topography alters current regimes and therefore, sediment-transport processes, influencing the patchy distribution of large sessile megafauna. The dissymmetric distribution and abundance of corals between opposite flanks of a canyon is a common feature reported from Lacaze-Duthiers, Cassidaigne, and Cap de Creus canyons in the Mediterranean Sea, Guilvinec, Penmarc'h, and Whittard canyons in the NE Atlantic and The Gully in the NW Atlantic. Similarly, distribution of corals and sponges at the heads of shelf-incising canyons seems to be related to strong currents that expose underlying bedrock in these areas. At a smaller scale, steep features of exposed rock, such as vertical wall sand over hangs, facilitate the settlement of the scleractiniancorals *L.pertusa* and *Madreporaoculata*.

In addition to currents and topography, substrate heterogeneity is a key factor contributing to the highly diverse faunal assemblage present in submarine canyons. Submarine canyons host a wide variety of substrate types, including mud, sand, hardground, gravel, cobbles, pebbles, boulders, and rocky walls, occurring either separately or in various combinations (Figure 55). Most species are restricted to either hard substratum (most scleractinians, antipatharians, most gorgonians, most sponges) or soft substratum (most pennatulids, some scleractinians, some gorgonians, some sponges). For example, in Pribilof and Zhemchung canyons (Bering Sea), gorgonians, and sponges were associated with hard substrate, while pennatulids were associated with soft sediment. In Bari Canyon (Adriatic Sea), denser sponge aggregations were found on rocks and dead corals than in areas with heavy sedimentation rates. In Halibut Channel, Haddock Channel, Desbarres Canyon, and The Gully (eastern Canada margin), observed species combinations were dependent on the dominant substrate type. Sponge diversity was also positively correlated with substrate heterogeneity in five canyons off the southeastern Australian margin.

Structure-forming corals can occur in dense patches, fields or reefs in canyons. Coral colonies can form mound-like features (bioherms) or are found attached to vertical walls, overhangs, drop stones, or any exposed hard substrata within canyons. However, patches or reefs, particularly those composed of scleractinians, often have a low density of live corals and a high amount of sediment between the colonies. In canyons, the ecosystem engineering role of cold-water corals and sponge fields has not yet been studied in detail, which contrasts with the significant data available for carbonate mounds and seamounts on the role of corals as autogenic engineers providing substrate, shelter and/or feeding place for associated species. Nevertheless, there are several examples of fish and invertebrate associations with corals in canyons. In the Bering Sea, rockfishes, sculpins, poachers, and pleuronectid flounders are associated with high densities of gorgonians, pennatulids, and sponges in Zhemchug and Pribilof canyons. In The Gully (NW Atlantic), was found a positive relationship between coral species richness and the total number of mega faunataxa, however, the abundance of fish was not correlated with the abundance of corals. Coral species richness was an important factor in explaining the variation in both fish and crustacean assemblages in north western Atlantic canyons. Is hypothesized that sea pen fields on deep banks off California (E Pacific) may have an important role as refuges for small invertebrates. In the canyons off Newfoundland, however, sea pen fields did not noticeably enhance the densities and richness of megafaunal assemblages.

Sediment instabilities and turbidity flows give rise to disturbance regimes in canyons that can affect the dynamics of some benthic populations and communities. For example, episodic disturbance events, caused erosive flows, and sediment- mixing processes linked to current modifications induced by the canyon topography, contribute to the instability of sediments, making conditions unfavorable to many infaunal species. As a consequence, differences in life-history strategies are reflected in species composition of the infaunal assemblages (e.g., nematodes) in different habitat types, with, for example, opportunistic species being more abundant inside canyon systems. Sediment removal from the shallower canyon regions toward the deeper margin areas can also cause a decrease in overall available. nutritional material. This decrease in food availability can lead to a progressive decrease in local abundances of benthic and demersal fauna, with a subsequent decline in overall biodiversity. Benthic communities may experience periodic cycles of disturbance, recolonization and eventual recovery of communities. For example, Hess et al. (2005) studied benthic foraminifera contained in a time series of samples taken in Capbreton Canyon (BayofBiscay, NEAtlantic) after a down-slope turbidity flow event. Their results suggest that populations of foraminiferans recovered inabout 6–9 months. Samples taken down-core in successive turbidity sequences contained nearly the same faunal elements as the surface assemblages. Thus, it appears that community structure of these benthic foraminifera is confined to a nearly stage of recolonization. In Nazaré Canyon (off Portugal), Paterson et al. (2011) found that frequent physical disturbance in the middle and upper sections of the canyon axis had a dramatic impact on foraminifera, with only certain species able to colonize and survive in these habitats. These two studies are testament to the influence that relatively high frequency (sub-annual) turbidity currents can have on determining benthic community structure in canyons.

7.2 Canyons as providers of ecosystem services

The Millennium Ecosystem Assessment (MA, 2005) identified the conservation of ecosystems and their environmentally- sustainable use as priorities to ensure the long-term well-being of the planet. To this end, understanding ecosystem services is essential. Ecosystem goods and services (hereafter, just services) refers to the socio-economic concept that places high regard on the benefits derived from ecosystem services that sustainably support human wellbeing. Consequently, the focus of conservation has shifted from the conservation and preservation of species for the sake of the species only, to the conservation of the benefits derived from ecosystem services (MA, 2005). Ecosystem services can be classified into four major categories: (1) supporting services: those functions that feed into the other services, (2) provisioning services: goods obtained directly from habitats and ecosystems, (3) regulating services: benefits obtained through the natural regulation of habitats and associated ecosystem processes, and (4) cultural services: societal benefits, for example in terms of aesthetics and education.

7.2.1 Supporting Services

Supporting services have an indirect effect, both physically and temporally, on human wellbeing, as they include the ecosystem functions (e.g., nutrient cycling, habitat provision, water circulation, or resilience) on which the other services are based. Submarine canyons provide several supporting services, through their role in sustaining marine food webs and providing a variety of habitats, including areas for larval settlement and recruitment. Canyons facilitate the transport of nutrients from the shelf to the deep basins, affecting the overall fauna labundance and biodiversity of an area, and play a role in the maintenance of provisioning services within canyons. The role of canyons as nursery and refuge grounds is important in maintaining these provisioning services. For example, populations of the red shrimp *Aristeusantennatus* in NW Mediterranean canyons undergo seasonal ontogenic migrations closely related to the geomorphology of the canyons. Is suggested that the large augment of nutrients transported during cyclic dense shelf- water cascading events provide an increased food resource that enhances recruitment of *A.antennatus*. The authors suggest that these cyclic natural events help mitigate the general increasing over exploitation trend of this species observed over the last six decades. The red-shrimp fishery is extremely important for the Fishermen's Guilds in the NES pain region. In 2014, the red-shrimp fishery generated over 14 million of Euros for Catalonia alone. Figure 53 shows the relationship between *A.antennatus* catches and the presence of submarine canyons, providing evidence of the supporting services offered by submarine canyons.

7.2.2 Regulating Services

Regulating services refer to benefits provided by natural regulatory functions of ecosystems through processes such as climate regulation, carbon sequestration, or detoxification of waste. Canyons play an important role in regulating carbon storage and waste detoxification. As conduits for transport of sediment and organic matter to the deep sea, canyons contribute to the burying of carbon by taking it away from the surface layers and hence, play a role in climate regulation. Typically, biogenic particles settling on the seafloor undergo cycles of transport and re-deposition, influenced by tidal, storm, and cascading currents. Eventually, these particles reach a permanent accumulation region in zones of low hydrodynamic energy. In canyons, specific hydrodynamic processes and higher particulate transport result in a significant cycling of organic carbon. This nutrient cycling service plays an important role in the gas, climate and waste regulation function, which in turn influences human health and productivity. Additionally, these same transport processes can remove pollutants from shelf areas, carrying them to the deep sea where they are buried, transformed, or assimilated through processes such as bioturbation, decomposition, and sequestration. The monetary value of these services is currently outside the market system, with the exception of gas regulation ($1.3109/year). Thus, the full monetary benefits of these regulating services have yet to be evaluated for canyon systems.

7.2.3 Provisioning Services

Provisioning services refer to the products obtained directly from the ecosystem, such as fish, hydrocarbons, minerals, or genetic resources. Submarine canyons can directly provide food resources through exploitation of the fish stocks and other species (e.g., crustaceans) occurring within them. However, most fisheries take place on the slopes adjacent to the canyons, where fishing is easier. In these cases, canyons can provide supporting services in the form of habitat, food, and nursery areas for commercial species (see Section Supporting services). Another provisional service of submarine canyons is as a source for cold-water corals harvested for jewelry. Canyons can also be a source of genetic resources. The deep sea is a particular target for biodiscovery because specific conditions (e.g., total darkness, low temperature, high pressure, and in some cases such as hydrothermal vents, very strong thermal gradients, and high concentration of metals) result in specific physiological and cellular adaptations of the fauna. These adaptations increase the likelihood of finding unique secondary metabolites that can be highly useful for commercial production of medicinally important compounds. The high "hit" rate in recent bio-discovery studies in the deep sea supports this prediction. Since the 1990s, almost 80% of novel marine natural products from invertebrates were derived from cnidarians and sponges. In a review of marine natural products, was emphasized that discovery of new marine-derived bioactive compounds are predominately from sponges. However, the importance of cnidarians as a source of these compounds is increasing, with an enormous unexploited resource yet to be explored. Deep-sea canyons are a potentially rich source of genetic resources because they have high abundances of cnidarians and sponges (see Section Canyon effects on benthic sessile fauna and infauna). Finally, the potential monetary benefits of offshore drilling for hydrocarbons are large. Although this industry has not yet developed in submarine canyons, the oil and gas industry has started to explore options for development in these areas (see Section Oil and gas exploitation for more details).

7.3.4 Cultural Services

Cultural services are non-material benefits provided by the esthetic, educational, scientific, artistic, and recreational aspects of the ecosystem. As part of the deep sea, the remoteness of submarine canyons and our relatively limited knowledge of their faunal communities greatly increase their interest and fascination. The mysteries largely hidden in the deep ocean fuel the imagination of civil society, including artists and scientists. Considerable amounts of funding are being invested in research to increase the understanding of canyon systems and their ecological function, followed by the promotion of awareness to promote canyon stewardship. In the last 10years, several national and international science projects fully or partially focusing on submarine canyons have been funded. Fascination with the deep-sea realm is not recent, as shown by the internationally renowned adventures aboard the submarine *Nautilus* in *Twenty Thousand Leagues Under the Sea* by Jules Verne (1870). However, current technology provides opportunities for civil society to explore, remotely, regions of the planet that were not accessible to most people until recently. Cabled observatories , such as Ocean Network Canada's in Barkley Canyon, provide a window for the public into the deep sea by offering online, real-time views of the canyon sea bed. Similarly, ROV cruises with real-time videos treaming online (e.g., as provided by NOAA Office of Exploration and Research and the Ocean Exploration Trust), help to provide this cultural service to a wide public. Through films (e.g., Blue Planetseries, BBC), books, *The Deep* by Claire Nouvian), exhibitions (e.g., *Deeperthan Light* produced by the MAR-ECO and other deep-sea Census of Marine Life projects; *The Deep*, produced by C.Nouvian), and online platforms (e.g., Oceans Network Canada—Learning; telepresence-coverage of expeditions on NOAA ship *Okeanos Explorer*), it is possible for many people to gain a better understanding and appreciation of the deep sea, with its fascinating habitats and life forms. Other "cultural" services, although not available in all canyons , are whale-watching tourism (e.g., Kaikoura Canyon, off NewZealand) and surfing competitions (NazaréCanyon,offPortugal). The ncreasein awareness about the deep sea and canyon ecosystems, including their value and the current and potential impacts they face, will likely result in an increased and significant social demand for management and conservation measures. Attempts have been made to assess public perceptions of the value of deep-sea ecosystems. A choice experiment showed that the Irish public would be willing to endorse a trawling ban in all areas where corals are thought to exist, and pay a personal tax of 1 euro per year in order to protect these habitats.

7.4 Fisheries importance of submarine canyons

Submarine canyons and seamounts are "milestones" in the marine bottoms having singular characteristics in relation to the surrounding bottoms (Wurtz, 2010). They are places that show high "geo-diversity". The improvement of our knowledge about marine bottoms, resulting from research undertaken over the past 20 years, is based on a number of scientific papers on marine dynamics and the consequences from the ecological and fisheries point of view, which can be summarized in the following three points:

1. - Orography: sharp profiles such as steep slopes, zones of narrow steps or valleys, cause fundamental changes in marine dynamics and the flows of energy transfers. The area of the Cap de Creus canyon, one of the most widely studied in the Mediterranean, allows us to know more about its functions as a structure situated between the continental platform and the slope. According to the abundant scientific information resulting from diverse projects carried out in this area, the regime of cold, dry winds during a part of the year favours the arrival of nutrients to the deep zones. The canyon is thus rather like an oasis, that is to say, a zone of protection and feeding for the species, including demersal species of commercial interest.

2. – The supply of nutrients to these deep zones allows the development of significant biodiversity along a gradient of physical parameters from the upper edge to the inner parts of the bottoms of the walls. Some groups such as gorgonians, white or deep corals and some sponges, considered as habitat-builder organisms when growing in "gardens", generate biogenic structures for shelter that enhance the protection factor for spawners and their recruitment offered by the canyon.

3. - Zones protected from certain fishing gears: because of their sharp profiles, canyons are zones protected from bottom trawling. Canyons therefore promote a kind of “natural zoning” in local fisheries, i.e. they spatially segregate different gears, allowing for long-line and some artisanal fisheries activities, both proportionately more selective than bottom trawling.

Another example of zoning in fisheries, in this case “artificial“, are the polygons of artificial protection reefs which, at the request of the artisanal fishing community, have mainly been deployed in the spanish Mediterranean sea by the Spanish General Secretariat for Fisheries of the Ministry for Agriculture, Food and Environment, with the aim of protecting sensitive bottoms of fishing interest, like *Posidonia oceanica* meadows in the Mediterranean. Like these artificial reefs, canyons fulfil the function of a kind of natural spatial marine planning for some fisheries.

Summing up, these three key factors describing the arrival of nutrient-rich waters inside a canyon, surfaces with structures of natural protection that offer several kind of bottoms, geogenic and biogenic, some with three-dimensional structures that form habitats and, finally, the fact that canyons are zones free from bottom trawling, allow us to see the important role canyons play as protected areas for spawning and breeding of marine species, some of them of fishing interest.

Company *et al.* (2008) defined the ecological and fisheries role of the canyons by offering the following comparison: “canyons would be for demersal fishing species the equivalent of upwellings for pelagic fishing species”.

Progress in the collecting of scientific knowledge has placed protection and sustainable use of submarine canyons on international agendas as a result of the efforts undertaken by countries, multilateral organisms, the European Union and leading organisations in conservation programmes such as the IUCN. Furthermore, the extensive possibilities for exchanging information that exist today help to build a favourable background for decisiontaking based on reliable data, targeting the sustainable use of the marine environment and the practise of responsible and sustainable ways of fishing, within the framework of close collaboration between coastal countries around the Mediterranean sea.

International meetings, such as the one on Focal Points for Specially Protected Areas within Barcelona Convention held in June 2010 in Istanbul (Turkey), or the one in Procida (Italy) organised by IUCN, gather experts who contribute the most up-todate knowledge, and constitute essential steps towards the establishment of Marine Protected Areas, and among them, those far away from shorelines, including areas beyond national jurisdictions. These meetings also call for collaboration between experts and agents in all the fields, scientists, but also experts in international law, focusing on governance and management aspects which need to be addressed (IUCN, 2010). They are quite definitely indispensable for shortening distances between objectives written into different international agendas, such as those introduced for 2012, or resulting from the Convention on Biological Diversity (CBD) or the recommendation on Marine Protected Areas issued at the V World-wide Parks

Congress celebrated in Durban (South Africa) in the context of the IUCN Program 2009-2012.

In this respect, Spain and the European Union are now making an important effort within the framework of the LIFE + INDEMARES 2009-2013 project, focusing on obtaining sound scientific knowledge on ten Spanish marine areas candidates for the marine Nature 2000 Network, two of which contain canyons: the Cap de Creus in the Gulf of Lion area, and Aviles Canyon in the *"Cantabrico" Sea*, (northern Spanish Atlantic Sea).

As part of this project, the Spanish High Council of Scientific Investigations (CSIC) and the Spanish General Secretariat for Fisheries have collaborated in obtaining the fisheries "footprint" for the area of study of Cap de Creus, where we can assert that the canyons are, generally speaking, favourable areas for a marine ecosystem-based management approach, in which some fisheries of low impact take place, excluding bottom trawling.

7.4.1 The fishing footprint in the area of the Cap de Creus canyon, Northeastern Mediterranean

Canyons, as privileged environments for marine ecology and for fisheries, are considered good fishing grounds. So this fishing interest should be made compatible to fisheries, improved on the basis of the best scientific knowledge and minimum impact. The exhaustive knowledge of the boats and fishermen as crucial stakeholders within the framework of the protection of canyons and their potential management plans is a crucial first step towards ascertaining, in advance, the compatibility between an area's protection and sustainable fisheries activity.

The fishing footprint is the result of three steps and can be credited to collaboration from units within the General Direction of Fishing Resources and Aquaculture, with assessment provided by experts in the previous handling of fisheries data. The first step focused on an exhaustive study of the fishing sector in the area, taking artisanal fishery, that cannot be tracked through vessel monitoring system (VMS), on one hand, and the rest of the fishing fleet on another hand, this time through VMS tracking, along several years monitoring; the second step then consisted of processing the data supplied by the Spanish Fishing Monitoring Centre and data obtained via the VMS; and, thirdly, processing of all the data by CSIC experts using the Geographic Information System (GIS).

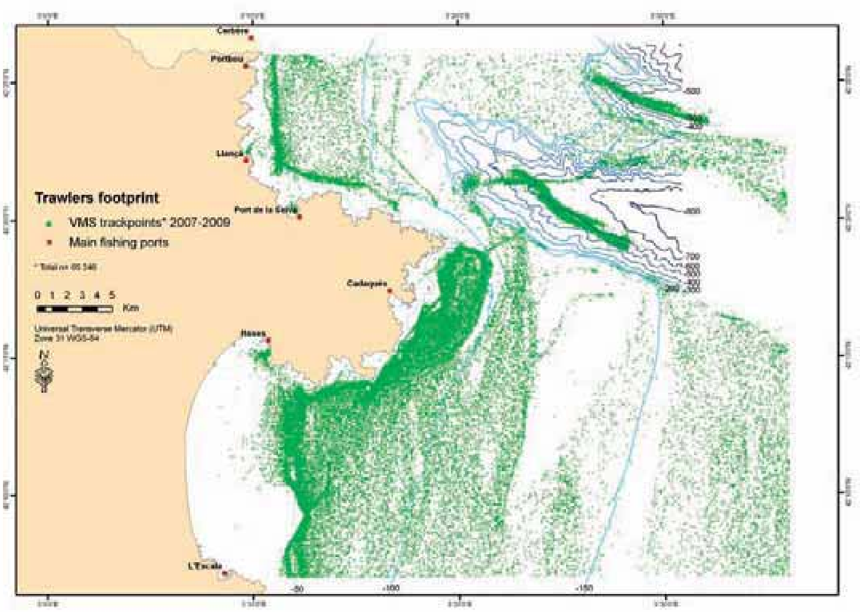


Figure 54 Physical and ecological characterization of the marine area of Cap de Creus

The work of the LIFE+ INDEMARES project in the area of the Cap de Creus canyon has come to a very logical conclusion: the most rugged bottoms are the best conserved, as they show much less fishing activity, specially no bottom trawling. The study of the "fishing footprint" in the area of the Cap de Creus was completed at the end of the research, but experts are now keen to learn about this footprint as soon as possible in order to plan the field work, since it can be very useful in identifying potential "hot spots" inside the areas of study, that is to say, the ones showing lower fishing intensity and, therefore, areas where sampling efforts should be concentrated.

In these circumstances, we see that the fishing footprint, as it gives evidence of the zones with lower fishing pressure, has turned out to be a useful tool in order to plan future work in the sea, always very complex and costly in both time and funds.

In the case of the Cap de Creus canyon research, close collaboration between the General Direction of Fishing Resources and Aquaculture and the team of scientists from the CSIC under the direction of Dr. Josep Maria Gili has allowed us to establish the fishing footprint in the Cap de Creus canyon within the framework of the LIFE+ INDEMARES project, using Geographic Information Systems (GIS) tools. The report also deals with the integrated concept of "*mιtier*" that combines fishing gear with objective species, geographic zones and seasonality, "covering the local tradition".

In this same sense, the concept of "*mιtier*" helps us to identify

precisely and without any doubt the fishing sector affected by the future MPA and therefore necessarily to be taken into account by stakeholders in order to tackle regulation of fisheries in the zones to be protected.

We should point out that, in the marine environment, fisheries, while not being the only human activity, are one of the most important to deal with for conservation purposes.

The basic tool in a management plan is zoning, applied in accordance with the precautionary approach, where fisheries are respectful of the habitat and carried out by the zone's traditional fishermen, and with some codes of best practices which can

be incorporated by means of clear and transparent agreements between the sector and the managers in charge of the protected area. This principle is to be applied to all the stakeholders affected by the MPA, including the fishing sector, one of the most deeply concerned by sustainable fishing, making well-conserved canyons possible in all their integrity and functionality, that is to say, harmonizing protection and conservation with sustainable use.

This could be considered as a kind of ecosystem-based management approach applied to the fisheries. Spain is precisely a leader in the case of marine reserves of fishing interest focusing on the enhancement of fisheries while protecting marine habitats in a similar scheme aiming to protect canyons and their traditional uses.

7.4.2 Fishing in other canyons

South of the Cap de Creus, in other areas with canyons like that of Palamos off the coast of Girona, or in the canyons in front of Cape Tinoso off the coast of Murcia, the fishing footprint has also been studied, while on the Alboran platform there are no true canyons, even though fishers talk about them as being rather deep "beaches" good for deep fisheries.

In the case of the Canyon of Palamos, south of Cap de Creus, the fishing footprint has been studied within the framework of the preliminary project for the possible creation of a marine reserve off Girona, in the surrounding area of the "Illes Formigues"- Costa Brava, since the head of the canyon is a zone of fishing interest in the northern part of the study area.

Fishermen are aware of the importance of these canyons in relation to fishing for red shrimp (*Aristeus antennatus*), of very high commercial value and whose extraction in the western Mediterranean developed fully from the 1940's or 1950's as gears began to reach greater depths (Bas, 1966). This fisheries activity with marked swings from year to year, due to the factor recently called "submarine waterfalls" by CSIC researchers, shows that the surface and marine bottoms present a greater connection than initially expected, though now already indicated in recent advances.

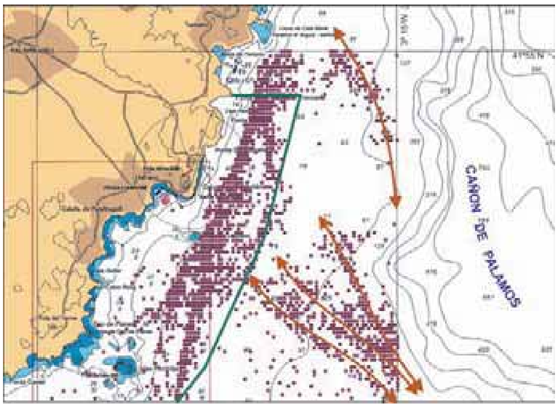


Figure 55 Trawlers in the Canyon of Palamos, northwest Spain.
Fishing footprint in the marine area of Illes Formigues - Costa Brava

Thus, the red shrimp would be subject to periodic processes of disappearance related to downward currents that displace the populations to deep waters, beyond 1.000 meters in depth. These privileged areas for recruitment, rich in nutrients thanks to the effect of these same currents, would seem to guarantee regeneration of the resource, subject to an important fishing effort, given its high value, and allow “re-appearances” of the fisheries with good results in catches, as a consequence of the refuge effect for species inside the canyon.

Similarly, the fishing footprint in the area in front of Cape Tinoso (Figs.53, 54 and 55), off the coast of Murcia, offers a clear spatial organization of fisheries, where the presence of trawlers clearly outlines the head of the canyons, whereas other gear such as drifting long-lines do not present this spatial concentration.

On the platform of the Island of Alboran (Fig. 56), no studies have yet been made on the fishing footprint, but traditional fishing grounds for red shrimp adopt the forms of the two beaches, called *“embarres”*, that run north and south around the island of Alboran, where bionomic cartography is the subject of a study forming part of the Life + INDEMARES project.

In this case, the existence of both the marine reserve and the fishing reserve of the island of Alboran, created in 1998 by the General Secretariat for the Sea, where regulated fisheries exist beyond the fully protected area around the island, known as the integral reserve, will definitely facilitate fishing activity regulations in the future marine protected area. Twenty-five years of experience in Spain with marine reserves policy show that sustainable fisheries in a marine protected area provide feed back for both conservation and production objectives.

Once again, the road map: reliable scientific knowledge from scientists and managers, and a sound governance scheme as drivers of the management tool. With this approach, the extraction sector should definitely be one of the most interested to participate, in order to have a management tool built on the best scientific knowledge of marine ecosystems and best practises, within the context of adaptative fishing management which would, no doubt, benefit all; fishermen, managers and, of course, society.

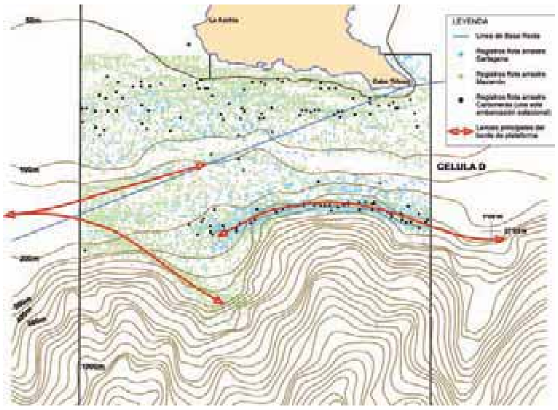


Figure 56 Trawling activity 2005-2010 off Cape Tinoso, southeast Spain, from *Fisheries activity and footprint in the area off Cape Tiposo (Murcia)*

Figure 57 Artisanal fisheries 2005-2010 off Cape Tinoso (Murcia)

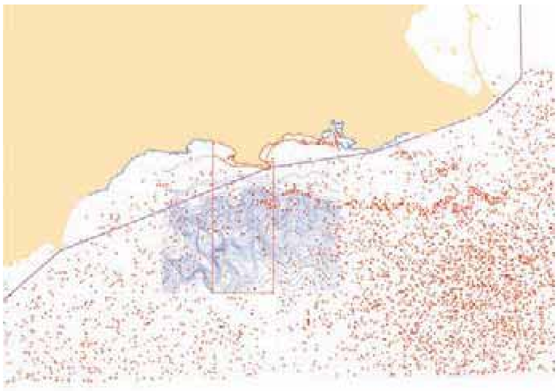


Figure 58 Drifting long-lines activity 2005-2010 off Cape Tinoso (Murcia)

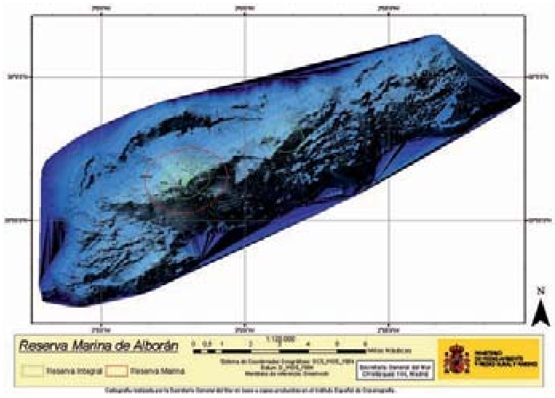


Figure 59 Map of the marine platform off the Island of Alboran, 2011, Marine Reserves, Spanish General Secretariat for the Sea. Geo data-base, compiled by Moran (2011).

7.4.3 Direct and Indirect Effects of Fishing

Among the human activities that can severely impact the deep- sea floor and associated biological communities, bottom trawling is arguably one of the main concerns, because of its physical impact, geographical extension, and recurrence. Submarine canyons are not an exception and the enhanced presence of marine life in and around some canyons results in these ecosystems increasingly being targeted by commercial fisheries, including bottom trawling and dredging. As part of the general offshore expansion of bottom-trawling fleets during the last decades, the rims of submarine canyons, from the shelf edge down to mid-slope depths, have been increasingly targeted. Large quantities of orange roughy (*Hoplostethusatlanticus*), blacks cabbard fish (*Aphanopuscarbo*), oreos (e.g., *Pseudocyttus maculatus*) and various macrourid (e.g., *Coryphaenoides rupestris*) species have been exploited from deep-sea habitats. Deep-sea fishes tend to have intrinsically low growth rates and low fecundity, meaning that sustainable exploitation requires a very low catch rate. Furthermore, there is evidence that fishing in these ecosystems may cause substantial damage to the fragile, long-lived, sessile fauna such as structure-forming corals and sponges. As a consequence, this exploitation has been compared to mining activities, because the resource is considered non-renewable on the scale of reasonable human lifespan.

In the NW Mediterranean Sea, an intensive fishery targeting the red shrimp *Aristeus antennatus*, has taken place for over six decades along the upper slope and around the deeply incised local canyons on the margin. The decrease of the yield per recruit, CPUE (catch per unit effort) and mean individual length over the last 20 years is probably a symptom of population changes induced by the intense exploitation. In addition to the impact on the biological communities, studies conducted in this area, within La Fonera (or Palamós) Canyon, have revealed that the trawling gear passing near and along the canyon flanks down to 800m depth significantly impacts the seafloor. Trawl gear produces extensive sediment resuspension (Figure 54), erosion, organic carbon impoverishment, and ultimately, results in enduring changes to sea floor morphology at the spatial scale of the entire continental margin. It is identified a loss in the bio available content of organic matter, mainly amino acids, along the trawled flanks of La Fonera Canyon, while is documented notable ecological consequences of intensive trawling. These authors found that trawling, by continuously stirring the soft sediment of seabed over the years, has led to an 80% decrease in abundance and 50% reduction in the biodiversity of meiofauna. Additionally, nematode species richness decreased by 25%, when compared to similar areas where no trawling occurs. Data also revealed that trawled sediments are impoverished (over 50% reduction) in organic matter content and have lower rates of carbon degradation (about 40%). These results suggest that continued deep-sea trawling represents a global threat to seafloor biodiversity and ecological health of submarine canyons, causing effects on their flanks similar to those resulting from agricultural plowing and human-accelerated soil erosion on land. Moreover, the impacts of trawling-induced re suspension of sediments are not restricted to fishing grounds, since re-suspended sediments are advected from trawled areas toward greater depths, concentrated within nepheloid layers, and deposited into canyons through sediment- laden density flows triggered by trawling gear along steep canyon flanks. Martín et al. (2008) through radionuclide dating of a sediment core collected at 1750m depth in the axis of La Fonera Canyon (NW Mediterranean), documented a doubling of the sediment accumulation rate in the 1970s, coincident with the rapid industrialization of the local trawling fleet. Puig et al. (2015) revisited the same canyon area a decade later and confirmed the two fold increase in the sedimentation rates during the 1970s, but also suggest that the accumulation rate during the last decade could be greater than expected, approaching ~2.4cmy −1 (compared to ~0.25cmy −1 pre-1970s).No submarine canyon in the world has been studied as intensively as La Fonera Canyon for the effects of bottom fishing gear, but given that canyons are often targeted by fisheries, it is likely that similar and other impacts have occurred and are occurring in other canyons elsewhere in the world. In Whittard Canyon (NEAtlantic), unusual peaks in nepheloid layer swith much higher concent rations of suspended particulate matter (1–8mgL−1) than normal(~ 0.075–0.5mgL−1) have been observed. Using VMS (Vessel Monitoring System) data from fishing vessels at Whittard Canyon, these peaks were linked to trawling activity. The direct and indirect impacts of trawling can affect cold- water corals and sponge fields. These two taxonomic groups are considered highly vulnerable, because they are usually slow- growing (up to 4–10mma year; e.g., Roberts, 2009 and references herein), long-lived and sessile, and thus very fragile and easily disturbed. Vulnerable Marine Ecosystems (VMEs), such as coral (e.g., *L.pertusa*) reefs and deep-sea sponge aggregations that can occur in canyons, are recognized as habitats in need of protective measures by several international organizations (e.g., OSPAR, ICES, and FAO). For VMEs threatened by trawling on continental slopes, the complex morphology of canyons might offer the last refuge. Fabri et al. (2014), for example, suggested that in the NW Mediterranean Sea, most current dense aggregations of the gorgonian *Isidella elongata* occur on the steep slopes of canyons unreachable to trawling. However, the fullex tent of the impact of trawling gear on non-target benthic fauna such as corals is unknown. Although baseline ecological data of the “pristine” ecosystem is often not available, long-term studies of certain areas and landing and discards data from fisheries provide information on the changes taking place in benthic communities. For example, Company et al. (2012) suggest that there is a canyon effect on the community structure of the benthic mega fauna of Blanes Canyon (NW Mediterranean), but that differing fishing pressures targeting the red shrimp *A.antennatus* on the margin and in the canyon may modulate the observed patterns. Trawling effects are also implicated in inducing changes to the trophic structure of benthic communities. The results of a comparative study of the benthic community on two margins (including canyons) affected by differing fishing pressures showed a predominance of mobile-predator scavengers and decrease of suspension -,filter-, and deposit-feeders in the areas of higher trawling intensity, compared with other areas where the trawling intensity was lower.

Long line fisheries also occur in canyon systems (e.g., sablefish *Anoplopoma fimbria* and groupers *Epinephelus* sp). Although this gear does not cause as much damage as trawling, when placed over coral habitats, the line can become entangled with the coral thus damaging the colonies during gear recovery. Additionally, ghost fishing is a well- reported problem related to lose gillnets or traps which continue to catch fish and damage other species.

7.5 Human activities impacting canyon ecosystems

In continuation of below, except fishing, four more major sources of impacts are threatening submarine canyon ecosystems: oil and gas exploration and exploitation; pollution, including marine litter, chemical pollution, and submarine disposal of tailings produced by land-mine activities; ocean acidification; and climate change-related stressors.

7.5.1 Oil and Gas Exploitation

Submarine canyons coincide with some areas targeted by the offshore oil and gas industry for exploration and development opportunities. Examples include potential economic deposits located off West Africa and the Campos Basin located on the continental slope of Brazil, which is currently under production by PETROBRAS and other companies. In Australia, an assessment was made by Harris et al. (2007) of the seafloor features most characteristic of offshore oil and gas leases. Surprisingly, nearly 24% of Australian submarine canyons occur in oil and gas leases even though such leases cover only 8.7% of Australia's EEZ (Exclusive Economic Zone). Thus, it would appear that, at least for Australia, submarine canyon habitats are positively selected for with regard to oil and gas leases, in comparison to other seafloor geomorphic features.

Over the last 10 years, several studies have focused on the effects of exploratory offshore drilling in response to the growing interest by the oil and gas industry to move operations further offshore. This offshore shift is especially true for countries such as the United Kingdom, Norway, Italy, Malaysia, Indonesia, and Australia, which number among the leading oil-producing countries. Results from these and previous studies suggest that discharge of drilling waste is the primary environmental concern of oil and gas drilling operations. Drilling discharges are composed primarily of dense particulate solids that settle rapidly and accumulate in sediments down-current from the platform. The rapid accumulation of these solids in the sediments has caused changes in benthic community composition (loss of rare species and increase in abundance of pollution tolerant species), decrease in abundances and diversity of communities and decrease in coral coverage among others. The effects of drilling discharge can also affect the biology, particularly growth and reproduction, of megafaunal species. For example, bentonite and barite particles may cause changes in reproduction and growth of scallops. However, other studies indicate that the effects of elements incorporated in discharge are mainly a physical stress, while chemical toxicity is not always described. Although studies specific to submarine canyons have not been conducted, the effects of drilling waste on benthic and demersal species is highly dependent on a number of local environmental variables (e.g., depth, current, and wave regimes, substrate type. Thus, it is expected that similar or even greater effects in canyons because of the presence of VMEs (e.g., coralreefs) and potentially restricted movement of pollutants due to current regimes in canyons. Experiment a land monitoring studies based on the exposure of *L.pertusa* to drill cuttings from oil drilling activities on the Norwegian continental shelf indicate that corals polyps tolerate well the enhanced particle deposition rates and suspended matter concentrations. However, a small pilot experiment indicated that coral larvae might be particularly vulnerable to high particle concentrations. The effect of accidental oil spills from deep offshore drilling (e.g., Deepwater Horizon oil spill in the Gulf of Mexico) could also be more severe given the physical and hydrodynamic nature of submarine canyons.

7.5.2 Canyons As Sinks for Marine Litter and Chemical Pollution

The London Convention (1972) and London Protocol (1996) legally banned the dumping of litter from ships. However, litter occurs in all marine habitats, from the intertidal to abyssal plains, entering the marine system from the coast (rivers, beaches) and through illegal dumping. Although dedicated and opportunistic studies on deep-sea marine litter have increased in the last decade, knowledge is still sparse. However, the data obtained to date from regional, as well as international, large-scale investigations, suggest that canyons are a major habitat for the accumulation of litter (Figure 57). The specific hydrographic patterns and increased down slope currents in submarine canyons result in canyons becoming hotspots of marine litter. A study comparing the accumulation of marine litter in different deep-sea habitats across Europe showed that litter densities in canyons were higher than in other physiographic settings, such as continental shelves, seamounts, banks, and mounds. In the Mediterranean, a study of marine litter on the slope, deep basin and canyons indicated that canyons preferentially accumulate light debris (e.g., plastic), which is transported downslope from the shelf in highly populated coastal regions. In Monterey Canyon (E Pacific) ,heavier litter tends to accumulate in high-relief outcrops or depressions, while soft plastics accumulate in areas where structure-forming corals provide relief on the seafloor (Figure 57). The effects of litter on the benthic fauna are little understood. However, impacts such as suffocation, physical damage of sessile fauna (e.g., corals, sponges, crinoids) and ghost fishing from discarded or lost fishing gear have been observed. The degradation of plastics into microplastics and their transport in the water column and accumulation in the sediments provides an additional source of concern. These microplastics are potential sources of toxic substances (e.g., persistent organic pollutants) and if ingested, may have lethal or sub-lethal effects on the fauna as well as pose a threat to human health through their bio-accumulation in the marine food web.

Investigation of chemical contamination of deep-sea ecosystems is increasing. Results show that chemicals are accumulating in deep-sea sediments, benthos, and mid-water fauna. The major contaminants of concern are persistent organic pollutants (POPs), toxic metals (e.g., Hg, Cd, Pb, Ni, and isotopic tracers), radio elements, pesticides, herbicides, and pharmaceuticals. The hydrodynamics of canyons favor the quick movement of labile material to the lower slope, where local benthic environments might become sinks of pollutants. In the NW Mediterranean, general accumulation patterns indicate that organisms collected inside Blanes Canyon had higher concentrations of POPs than individuals collected on the adjacent open slope. These inputs could be the consequence of enhanced vertical transport of hydrophobic particles associated with chemical pollutants, the dispersal of which is driven by local hydrodynamic processes that regulate fluxand sediment re-suspension patterns.

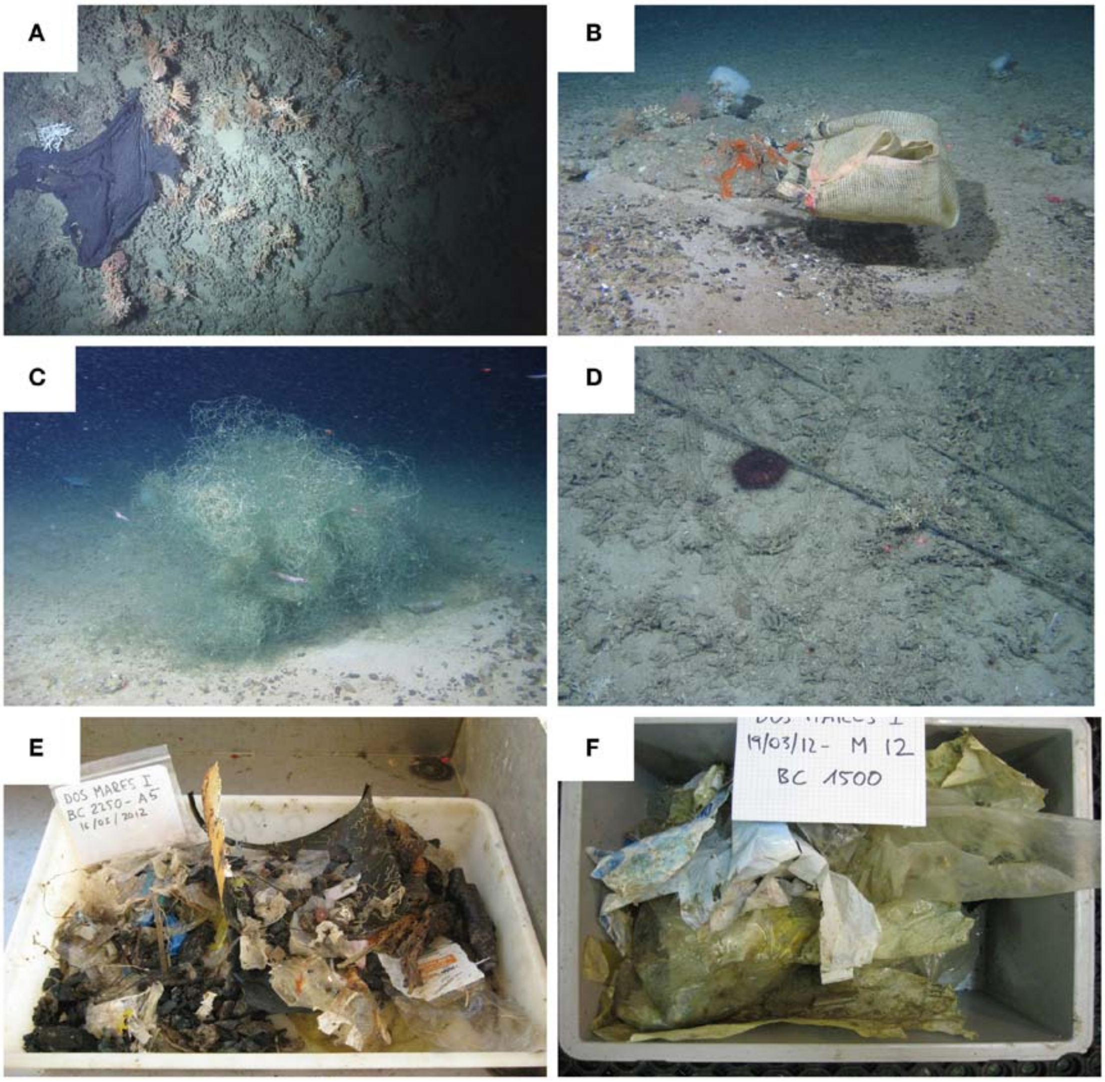


Figure 60 Images of marine litter found in different submarine canyons.

7.5.3 Canyons as Areas for Mine Tailing Disposal

Land-based mining produces large volumes of waste in the form of non-processed overburden rock and processed fine particulate tailings. The tailings (fine-fraction slurry) usually account for a very high proportion of the ore (e.g., 99% for copper and 99.99% for gold, MMSD, 2002). Some tailings can, additionally, include process chemicals (e.g., floatation or flocculation chemicals) and heavy metals, and in some cases, very sharp particles resulting from the crushing process. Although most mines use conventional land-based damns to store tailings, there is an increasing interest in submarine tailing disposal (STD), including deep-sea tailing placement (DSTP). DSTP occurs where a pipe is submerged below the mixing layer(>100mdepth), and where a turbidity flow is created that transports the tailings down to the deep seafloor. The environmental impacts of DSTP can include: (1) smothering of the benthic ecosystem in the deposition area through hyper-sedimentation; (2) chemical toxicity from metals or processing chemicals; (3) modified organic matter content and porosity of sediments (grain size and angularity) that can affect feeding and recolonization; (4) formation of sediment plumes and increased turbidity which may impact pelagic organisms and (5) risk of slope failure and re-suspension of tailings. Currently, seven mines across the world conduct DSTP, three in Papua New Guinea, one in Indonesia, one in France, one in Greece, and one in Turkey. When considering DSTP, canyons are often proposed as preferential locations because of their natural capacity to act as conduits to deep basins. For example, the Ramu Nickel Project in Papua New Guinea discharges tailings at 150m into Basmuk Canyon, with a final deposition at 1500m. The Indonesian Batu Hijau copper and gold mine has discharged its tailings at 125m depth into Senunu Canyon since 2000, with final deposition between 3000 and 4000m depth. This DSTP is the deepest deposition of tailings in the world. In France, the alumina plants in the Marseilles area (NW Mediterranean) that process bauxite have discharged the red-mud residues produced by this process into Cassidaigne Canyon since 1967. The pipe is situated at 330m depth and the red-mud deposit extends more than 50 km from the outflow into the abyssal plain. Excess concentrations of iron, titanium, vanadium, and chromium are recorded on the seafloor. *In situ* observations of sessile fauna (e.g., gorgonians) covered by the red mud show signs of tissue necrosis, which indicate that there is a negative, or even lethal, effect of the accumulation of red mud on the megafauna. Nevertheless, settlement of new coral colonies has also been observed, perhaps in response to the decrease in red- mud outflow since 1988, when one company stopped discharging tailings.

7.5.4 Geo-hazards and mass wasting

On the other hand, submarine canyons can affect human activities. Where the canyons deeply incise the continental shelf and develop close to the coast, the prominent headword erosion can provoke collapse of coastal infrastructures. Such failures have the capacity to create tsunamis, and may even cut back to the coast and cause direct damage to coastal shore infrastructure or initiate coastal landslides.

Several near-shore areas of the Mediterranean Sea (Alboran, Aegean, Tyrrhenian and Ionian Seas), southern Black Sea and the northern Sea of Marmara are characterized by very narrow shelves and by canyons initiating very close to the coastline. Such settings are especially prone to tsunami generation by failures of canyon heads. Striking examples are the 1977 Gioia Tauro (Italy) and 1979 Nice (France) landslide-tsunamis at canyon head. In both cases, the failures were induced by civil engineering activities linked to harbor development and caused waves several meters high that resulted in severe damages and also in human casualties in the latter case. Comprehensive and detailed analyses of submarine canyon heads, including the geotechnical properties of the seafloor and sub-seafloor, are a strict requisite in refining the current geo-hazard assessment models to inform stakeholders with concrete protection measures.

Moreover, canyons can also capture flash floods and channelize strong turbidity currents, that are able to reach down-canyon velocities >10 m/s with the potential to break pipelines and cables, now so essential to maintain our lifestyle.

It is widely accepted that mass wasting events do play an important role on canyon initiation and evolution. Failures at midslope locations followed by upward retrogression may initiate canyon formation. In addition, canyon flanks become unstable, mainly due to basal erosion produced by gravity flows. This process is the cause of canyon widening, as witnessed by the large number of complex scars and instability features observed on canyon walls.

Such slope sediment failures may also trigger tsunamis. For failures on the open slope, landslides with the following characteristics are usually considered to trigger tsunamis of significant height: (1) shallow-water to intermediate depths (<1,000 m); (2) significant volumes (>2 km3); (3) stiff cohesive material (e.g., consolidated clay); and (4) rapid initial acceleration of the failed material. Of course the combination of these factors is crucial in determining the magnitude of the generated waves, given that even a small volume in very shallow water may produce higher waves than a very large volume in deep water. Most failures in canyons are much smaller than the 2 km3 mentioned above, but failures of canyon heads may occur very close to the coast and in shallow waters.

CHAPTER 8

GOVERNANCE AND MANAGEMENT OF SUBMARINE CANYONS

There is a range of legal and institutional frameworks for governing and implementing the conservation and sustainable use of marine systems. Despite the complexity of canyon management and conservation, in recent decades, some of these frameworks have been used to instigate conservation and management measures in different regions, and new frameworks are being proposed.

8.1 Legal Frameworks and Other Tools for Canyon Conservation

In 2008, the 9th meeting of the Conference of the Parties to the Convention on Biological Diversity (CBD, 2008, COP9) adopted seven scientific criteria for the identification of Ecologically or Biologically Significant Marine Areas (EBSAs) (annex I, decision IX/20); these are, (1) uniqueness or rarity, (2) special importance for life-history stages of species, (3) importance for threatened, endangered or declining species and/or habitats, (4) vulnerability, fragility, sensitivity, or slow recovery of ecosystems, (5) biological productivity, (6) biological diversity and (7) naturalness. Under these criteria and based on the specific characteristics of canyons, the CBD suggested that submarine canyons could be classified as priority areas for conservation on many continental margins areas (Davies et al., 2014). Similarly, the United Nations Food and Agricultural Organization (FAO, 2009) adopted similar criteria to identify VMEs. The VME concept has gained prominence following a resolution of the United Nations General Assembly (UNGA, resolution.61/105) to seek the protection of VMEs on the high seas and in areas of national jurisdiction (Weaver et al., 2011). Examples of VMEs include canyon habitats, as well as the coral reef and sponge aggregations that are sometimes found in canyons (FAO, 2009). These two conservation initiatives, as well as other international initiatives, are providing a platform for Regional Fisheries Management Organizations (RFMOs), Regional Seas Conventions and Action Plans (RSCAPs), and other proposals developed in the past 10 years (Jobstvogt et al., 2014) to provide protection for species and habitats that are important for sustainable marine ecosystems. The aim is to strengthen cooperative work in the development of a common roadmap under the coordination of the United Nations Environment Program (UNEP-MAP-RAC/SPA, 2010). Canyon systems, by their association with continental margins, are more often found in EEZs, where the concepts of EBSAs and VMEs are neither always nor consistently applied by nation states. Nonetheless VMEs have been identified in canyons on the Mediterranean margin (Fabri et al., 2014).In Europe, the Oslo-Paris Convention (OSPAR)from 2005 provides a legal mechanism in the northeast Atlantic area to protect several deep-sea habitats, including those submarine canyon habitats where cold-water scleractinian reefs (i.e.,dominatedby *L.pertusa*) are present(OSPAR, 2005).

Most submarine canyons are located within Exclusive Economic Zones (EEZs), which gives individual nation states the authority to control all extractive activities in their area (e.g., fisheries, oil and gas), thereby these states potentially offer protection to canyons through conservation and management measures such as Marine Protected Areas (MPAs) or fisheries management tools such as spatial/temporal closures of areas or gear restrictions. However, international agreements concerning the rights of free navigation must also be acknowledged in the development of management measures that include such area-based protection regimes. The legal framework of marine environmental protection is complex given the different levels of legislation (international, national, and regional) and varies widely depending on the countries involved. The complexity of governance depends mainly on the canyon's location. In the case of a cross border location such as Capbreton Canyon (France/Spain, Bay of Biscay) or a large area of international waters such as in the Mediterranean region, the regional disparities in governance and institutional structures make it difficult to find agreements to ensure a sustainable management of ecosystems. States have no mechanisms to create globally-recognized MPAs and reserves on the high seas. Instead, there is a patchwork of bodies, including RFMO that set policies for specific areas of the ocean or specific activities (such as fishing for tuna).However, those bodies lack the legal mandate necessary to establish MPAs. Nevertheless, there are several examples of areas where progress has been made in the protection of canyon habitats.

8.2 Examples of Current Canyon Conservation and Management

In Canada, The Gully MPA, located 200km offshore Nova Scotia, was created in 2004 under Canada's Ocean Act. The Gully MPA, covering an area of 2364 km2, includes three zones of protection based on conservation, management and research objectives. The Gully Advisory Committee, composed of representatives from academics, industry and non-government organizations, provides advice and information to the government on the MPA and related activities. In the Northeastern United States of America (USA), in addition to a network of habitat closed areas implemented by Regional Fisheries Management Councils (RFMCs), the New England Fishery Management Council (NEFMC), and Mid- Atlantic Fishery Management Council (MAFMC), added two canyon habitat closures (Oceanographer and Lydonia canyons) within Amendment 2 of the Monkfish Fishery Management

Plan. These closures were implemented as a precautionary approach to prevent impacts from the development of an offshore monkfish (*Lophius* sp.) fishery on Essential Fish Habitats (EFH) and deep- sea canyon habitats. Another example of fisheries management decisions benefiting preservation of canyon habitats is also in the western North Atlantic, off the east coast of the USA. Conservation measures designed to protect vulnerable marine species, such as deep-sea corals that occur in canyons provide a level of protection to the canyon as a whole. The MAFMC has approved the deep-sea corals amendment to protect known or likely coral habitat while limiting negative impacts to commercial fisheries operating in the region.Magnuson-Stevens Fishery Conservation and Management Reauthorization Act (Public Law 109–479) gives the RFMCs the authority to designate zones where, and periods when, fishing may be restricted in order to protect deep-sea corals from the impacts of fishing gear. The MAFMC considered various alternatives, and two spatially overlapping coral protection zones were selected as preferred options. The broad coral zone prohibits fishing in regional waters at depths of 450 m and greater, out to the limit of the EEZ. Discrete coral zones define specific areas where corals are known to occur or are highly likely to occur based on results of a habitat suitability model. The boundaries of most discrete zones outline large portions of submarine canyons. Under this amendment, all bottom-tending types of gear used in federally managed fisheries are prohibited in and around deep-sea coral habitat (i.e., canyons), with the exception of the deep-sea red crab (*Chaceon quinquedens*) trap fishery. This recent management recommendation in the western North Atlantic, if approved, will protect approximately 99,000 km2 of seafloor in the Mid-Atlantic region (East coast of the USA, Virginia to New York), including 15 canyons. Final approval is expected in late2016. A similar situation can be found on the Eastern margin of the Atlantic, where Explorer and Dangeard canyons are part of a United Kingdom Marine Conservation Zone (MCZ). This conservation measure was put in place with the specific aim of protecting cold- water coral reefs, but as a result large parts of the canyons are protected.

In the Mediterranean Sea, effective governance of canyon systems requires cooperation at various levels, ranging from international conventions to regional initiatives for environmental protection (Cinnirella et al., 2014). The European Council has adopted management plans for specific Mediterranean fisheries, in areas totally or partially beyond the territorial seas (including high seas) and affecting canyon habitats. Such plans include the prohibition of fishing with trawl nets and dredges in certain areas, and at depths below 1000m (EC Regulation 1967/2006). The Regional Activity Centre for Specially Protected Areas of Mediterranean Importance (SPAMI), under the Barcelona Convention agreements, has set up the legal framework to conserve marine habitats including submarine canyons (RAC/SPA, 2010). In the French part of the Mediterranean basin, three MPAs have been created to protect cold-water corals: the “Parc Marin du Golfe du Lion” (decree 2011-1269) including Lacaze-Duthiers, Pruvot and Bourcart canyons; the “Parc National des Calanques” (decree 2012-507) including Cassidaigne Canyon with specific regulations; and the “Parc National de Port-Cros”(decree 2012-649) with extension of the adjacent bathyal seafloor. In addition, the General Fisheries Commission for the Mediterranean (GFCM) established a fishing-restricted area off the French coast in the Gulf of Lion, including Montpellier, Petit-Rhône, and Grand- Rhône canyons in 2009 for the Mediterranean. This directive involved the regulation of certain demersal fishing gears and aimed to protect spawning aggregations and deep-sea sensitive habitats (GFCM, directive no. 33/2009/1, IUCN and UNEP- WCMC, 2016). In Spain, Protected Areas, Marine Reserves and Marine Reserves of Fishing Interest have been established, but these protected areas include only a few submarine canyons.

In 2012, the International Union for Conservation of Nature (IUCN) published a book on Mediterranean submarine canyon ecology and governance, which was based on the conclusions of several workshops focusing on Mediterranean governance. It was recommended to Mediterranean countries that a precautionary principle be applied to the canyons under their jurisdiction, and to include canyons in national, regional and international strategies forMPAs. The increasing role of non-governmental organizations (NGOs) in calling for improvement in canyon management has resulted in investigations of the most vulnerable submarine canyons, and in some cases protection measures have been proposed. For example, in 2011, Oceana (i.e., nonprofit international organization focused solely on the protection of the oceans, http://eu.oceana.org/en/about-us) published a new proposal for the protection of the Mediterranean vulnerable areas called MedNet. This proposal contained 28 submarine canyons (e.g., Bejaia Canyon, Algeria; Gulf of Lion submarine canyons, France and Spain; Bari Canyon, Italy amongst others) and included a detailed review of their main characteristics and current status of conservation initiatives. Some of these proposed canyons (e.g., Cap de Creus Canyon and Lacaze-Duthiers Canyon) have now been classified as Sites of Community Importance (SCI) under the EU Habitats Directive.

Although progress has been made to combine both marine conservation and fisheries management, it remains fragile due to disparities in regional governance and institutional structures between countries (De Juan et al., 2012). These authors highlight the complex jurisdictional situation of international waters in the Mediterranean Sea and mention the need for cooperation between coastal states with a regional operational strategy to achieve a sustainable management of ecosystems. The case of Capbreton canyon in the Bay of Biscay (NE Atlantic) provides an example of the difficulties that cooperation must overcome. Capbreton canyon extends from French territorial waters in to the EEZ of both France and Spain, and is regulated through several management measures. In the French part, these measures were first established in 1985 (Ord.n◦401985) at the request of local French fishermen and included fishing restricted areas for gillnets, and subsequent expansion to include restriction areas for pelagic and benthic trawlers. Most of the restricted area lies within the French Territorial Sea, but part extends into the French EEZ. The French restrictions in the EEZ area, however, do not apply to foreign vessels. The extension of such an area into the EEZ raises the questions of legality, enforcement, and monitoring for scientific purposes. Additionally, the cross border location between France and Spain of Capbreton Canyon makes fisheries management even more complicated, making agreements on trans-boundary cooperation difficult. Proposals for a management plan of a “Capbreton case study” were discussed between stakeholders during European project GEPETO (http://gepetoproject.eu/), which aimed to improve future fisheries management in the south European Atlantic coast region.

8.3 Global Submarine Canyon Protection Status

A recent review of global seafloor geomorphic features, based on the analysis and interpretation of a modified version of the SRTM30_PLUS global bathymetry grid, included a new assessment of submarine canyons and associated geomorphic statistics. The database that underpins the analysis of Harris et al. (2014) provides the information needed to estimate the area of canyons within each country’s EEZ as well as the area of canyon currently protected within MPAs. Here, we provide an analysis using Arc GISESRI tools on the proportion of canyons included in MPAs at the global scale. Statistics included the area estimates for 9477 individual canyons covering a total area of 4,393,650km2 (i.e.,1.2% of the total ocean area).

In order to estimate the area of canyons within EEZs (i.e., canyon area that can be protected within the jurisdiction of individual countries, as opposed to those located in the high seas or areas beyond national jurisdiction), global EEZ boundaries downloaded from the VLIZ database were used. In addition, a summary of global MPA boundaries was downloaded from the IUCN and UNEP-WCMC database (IUCN and UNEP- WCMC, 2016) and used to calculate the areas of canyons within MPAs. Results showed that of the overall 4,037,764.35km2 of sea floor found in submarine canyons in EEZs (91.9% of canyon area), 13.6% of canyon areas are protected (with at least 10% of their area) within an MPA. Only 10.3% of all canyons are completely protected (100% of their area) within an MPA.

This exercise identified 1956 canyons within MPAs. Of the 191 countries / jurisdiction with submarine canyon(s) in their waters, 163countries (83% of the total) have less than 10% of their submarine canyon(s) protected within an MPA. Only 12countries (6.3%) have 100% of their submarine canyons covered by MPA protection. From these last 12 countries / jurisdictions,10areoverseasterritoriesof France and the United Kingdom (e.g., British Indian Ocean, Glorioso Island, Ile Europe, see Annex for more detail) while the other two countries (i.e., Dijibouti and the Democratic Republic of Congo) have protected the only canyon they have in their waters(Annex1). In terms of numbers, the United States and New Zealand protected the highest number of canyons (117 and 54 respectively). Indonesia and the Philippines had the highest number of canyons within their EEZs (576 and 265 from which 20 and nine were protected respectively, Annex1). Notably, these results only reflect those canyons protected by management provided under MPA authority . However , there are other mechanisms in place that offer other protective measures (i.e., world heritage area marine park and fisheries management areas). Yet, no standardized world database exists that includes all protected canyon areas. Therefore, some level of worldwide synthesis, although difficult to achieve, is needed to assess the conservation actions undertaken for canyon protection. The data (see detailed Figure 61 of the Mediterranean Sea) also reveal that most of the marine conservation measurements have focused on shelf ecosystems, while the vast majority of continental slope areas around the world (where submarine canyons are found) are still without any regulations to prevent them from pollution and human exploitation.

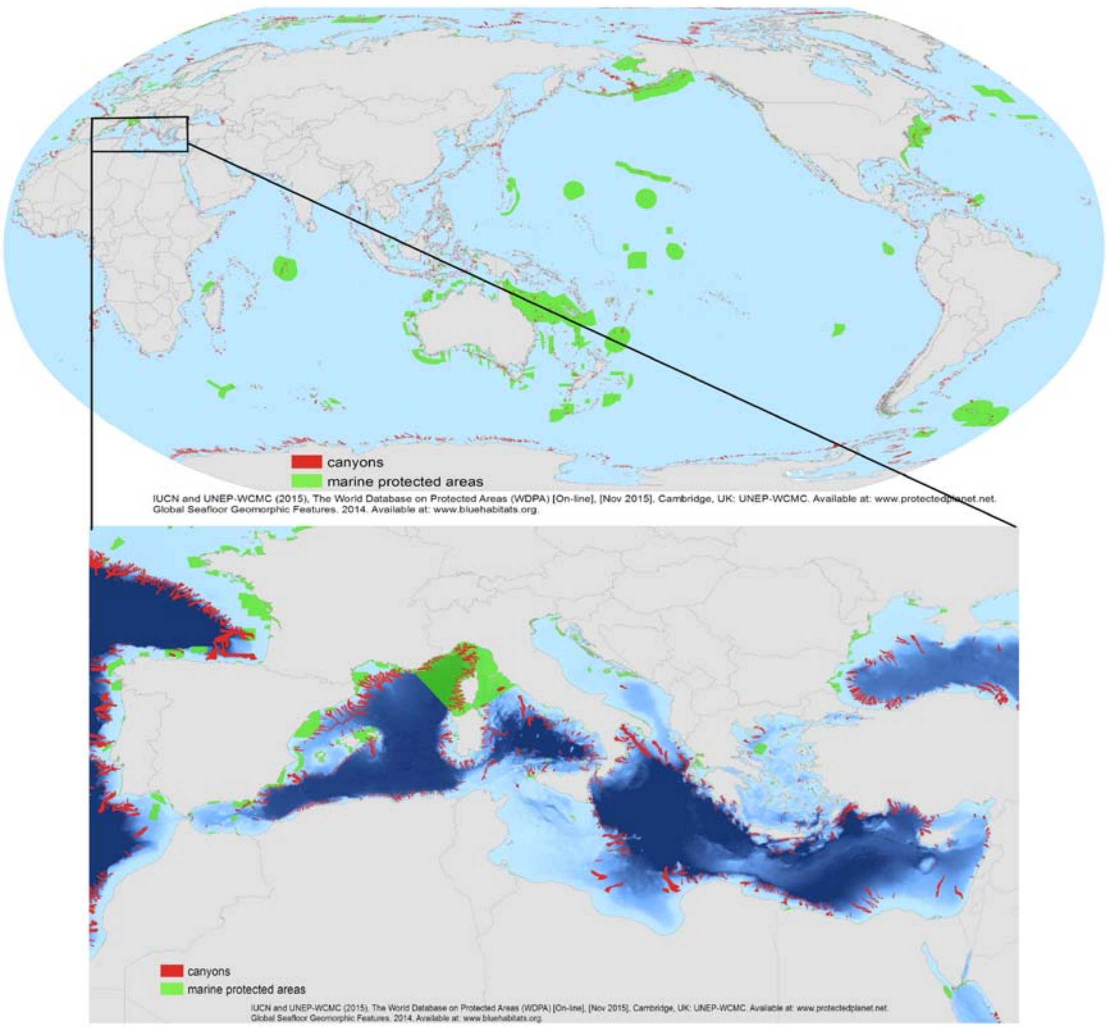


Figure 61 The global map showing submarine canyon distribution (in red) and Marine Protected Areas (MPAs) (in green)

Conclusion

The submarine morphology of ocean basins and margins discussed here illustrate the processes that have generated it. The analysis of the seascape, combined with sub-seafloor studies, is necessary to understand the mechanisms of continental margin evolution. Currently, multibeam echosounders are acquiring unprecedented highly detailed seafloor images. As a consequence, our knowledge of seafloor sculpting processes is improving rapidly.

The present seascape of Mediterranean basins is mainly controlled by neo tectonic processes and fluvio-sedimentary systems. Among the latter, the deposits and sediment bypass structures related to the activity and inputs of the largest rivers stand out. Because of its geographic and geologic variability, the Mediterranean may be used as an almost perfect laboratory for studying landscaping processes on submarine environments.

More specific

— (1) The majority of present-day Mediterranean canyons are, like the majority of rivers on land, mostly superimposed on tectonic lineaments, inherited either from earlier geological evolution, or, in the case of the Western Mediterranean Sea, from the various continental margin creation or re-activation periods (rifting of the north-western basin, rifting of the Alboran and Tyrrhenian Seas). Some canyons are, however, closely controlled by surrounding active tectonic, which makes strong imprints on the continental margin fabric and evolution (e.g. central Ligurian margin, Algeria, Southern Calabria, Western Peloponnesus, Crete, Southern Turkey).

— (2) Most of the upper domains of these features have been deeply eroded by retrogressive mechanisms and in aerial conditions, during the Messinian crisis when the sea level was several hundred meters lower than today (possibly up to 1.5 km locally).

— (3) In contrast to the majority of Mediterranean canyons, the Ebro, Rhone and Nile Rivers canyon systems are composed of active canyons and channels cutting, and running across, deeply sedimented platforms and continental slopes. These canyons may be, though not necessarily, locally superimposed on, or inherited from, previous canyons (e.g. Gulf of Lion). Alternatively, they may have been created in response to climatic and/or eustatic fluctuations (e.g. western Nile canyons).

— (4) In all cases, important amounts of erosion sediments are transported and distributed to the deep sea through these canyons, which in turn act as conduits for nutrients to the deep sea, particularly nearby coastlines bordering mountain chain areas, and may thus act as hot spots for biological processes.

— (5) Along several north African margin segments, such as off Libya and partly Maghreb, the canyons are almost disconnected from any river providing regular input, and may consequently only act as temporary pathways for sedimentary mass flows.

As regards the importance of submarine canyons, due to continuous demand for minerals, fish and genetic resources and regarding carbon deposit, international interest in canyons is increasing. However, many knowledge gaps remain in many regions regarding abiotic and biological processes in canyons. These issues must be addressed in order to provide the robust scientific knowledge necessary for effective management and conservation. This review demonstrates the need for further investigations to increase our understanding of community structure and ecosystem functioning within and around canyons. Future survey efforts need to incorporate rigorous and standardized sampling to obtain information regarding microhabitats, current flow, and organic matter input within the broad-scale habitat features. Such environmental data are required to better determine the mechanistic factors that affect the diversity, abundance, and distribution of fauna associated with these deep-sea habitats. There are new technologies and analytical methodologies that need to be used to efficiently and effectively provide the scientific understanding of canyons that is required.

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